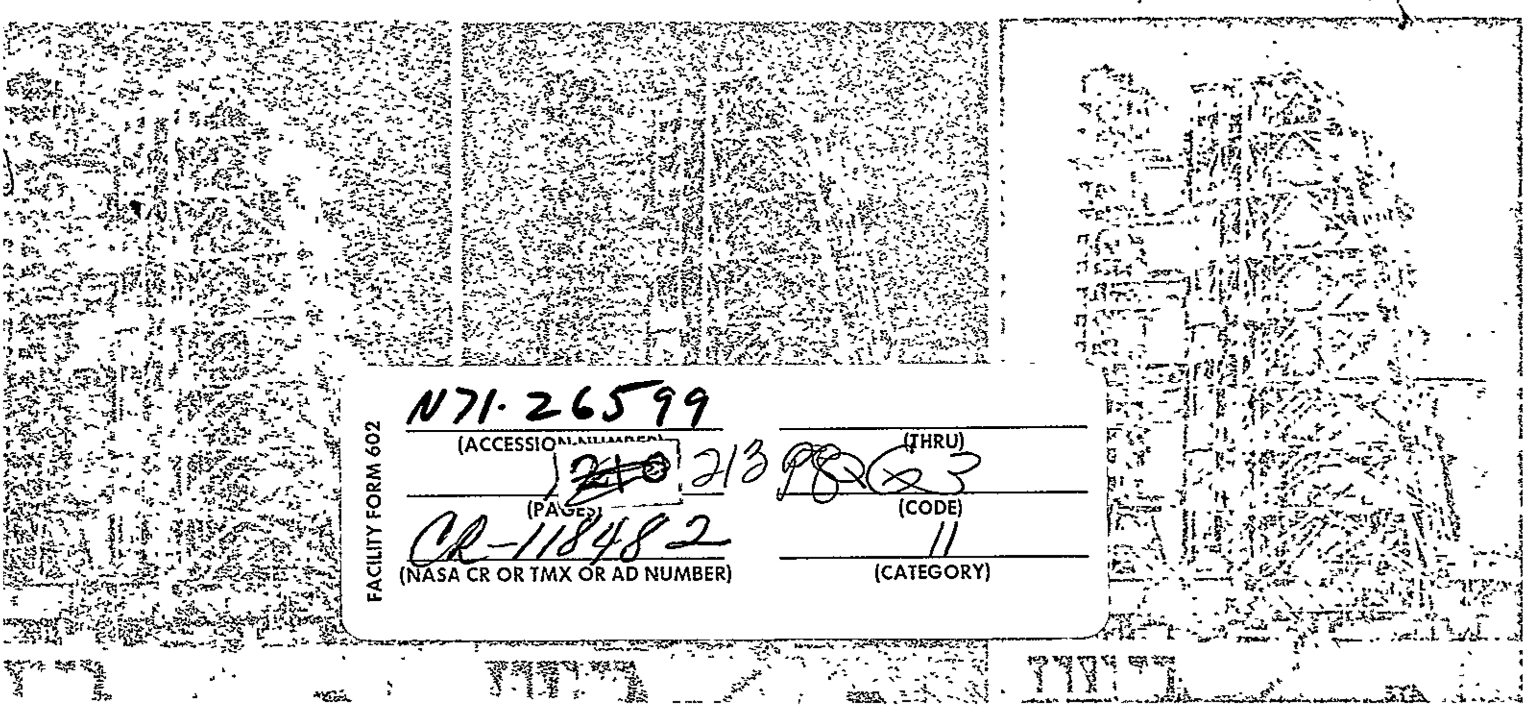

FINAL REPORT ON DEVELOPMENT OF BONDING AND GROUNDING CRITERIA FOR JOHN F. KENNEDY SPACE CENTER

VOLUME II: EVOLUTION OF BONDING AND GROUNDING CRITERIA AND ON-SITE EVALUATION OF BONDING AND GROUNDING PRACTICES

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16. Abstract

Volume II of this report contains a summary of the efforts on the individual tasks in the evolution of the bonding and grounding criteria contained in Volume I. Notable among the efforts reported in this volume is the on-site evaluation of the current implementation of bonding and grounding at KSC. Other tasks reported included a review of existing bonding and grounding practices for KSC and other installations, a definition of hazard conditions at KSC, a definition of required changes, and the updating of existing criteria. Appendix A contains a mathematical model of a wideband ground system, Appendix B, a computer program (in Fortran IV) for computing the characteristics of ground cables in conduit, and Appendix C, a set of ground rules for EMI reduction.

17. Key Words Bonding, Grounding, EMI, EMC, Nonlinear Junction Reradiation, LC-39, Hazards (Shock, Lightning, Explosion, EMI)	18. Distribution Statement UNCLASSIFIED-UNLIMITED

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PREFACE

This report describes the studies, analyses, and measurements performed under Contract NAS10-6879 for the development of bonding and grounding criteria for the John F. Kennedy Space Center, Florida.

The report is organized into three volumes, the contents of which are shown in the following table. This table includes the title of each task, the Contract Implementation Plan (CIP) Task Number, the Proposal Task Number, and a short synopsis of each reported task.

VOLUME I - BONDING AND GROUNDING CRITERIA

Section	CIP Task	Title	Proposal Task	Synopsis
1 2 3 4 5 6 Appendix A	 F H	Introduction Reference Documents Requirements Quality Assurance Preparation for Delivery Notes Rationale for Bonding and Grounding Criteria	11 Modify & Update Existing Standards 12 Update Criteria 14 Prepare Final Report Draft	This volume includes the criteria and standards which are the subject of the contract, using existing standards as a point of departure.

VOLUME II - EVOLUTION OF BONDING AND GROUNDING CRITERIA AND ON-SITE EVALUATION OF BONDING AND GROUNDING

Section	CIP Task	Title	Proposal Task	Synopsis
1 2	 A	Introduction Review Bonding and Grounding Standards	1A Review of KSC Bibliography 1D Review of Standards other than KSC 2 Reconcile KSC & Other Standards	Current literature was reviewed to determine methods of bonding and grounding employed at KSC and elsewhere.
3	B	Evaluate On-site Bonding and Grounding	1B Study of KSC Environment 1C Define Problem Areas 3 Prepare on-site evaluation procedures 4 Perform on-site evaluation	The bonding and grounding for LC-34, LC-37, and LC-39 were investigated for current condition and implementation. Ground resistance and resistivity measurements were made at selected points. Noise measurements in the time and frequency domains were made during dynamic tests on Apollo 13.
	C	Define Hazard Environment	1C1 Define Lightning Hazard 1C2 Define Explosion Hazard 1C3 Define EMI Problems & Hazards 1C4 Define Shock Hazards 5 Define Total Hazard Environment	

VOLUME II - EVOLUTION OF BONDING AND GROUNDING CRITERIA AND ON-SITE EVALUATION OF BONDING AND GROUNDING (Continued)

Section	CIP Task	Title	Proposal Task	Synopsis
5	D	Define Areas Requiring Correction	6 Identify on-site deviations & hazards 7 Define anomalies 8 Refine hazard environment.	This section reflects areas requiring correction in the relevant KSC specifications and standards as well as on-site anomalies found during the evaluation.
6	E	Present Midterm Report	9 Midterm Report 10 Consolidate comments from Midterm into Baseline	This report was presented at KSC on 20 March 1970. Thirty copies of the presentation material were transmitted to KSC on 6 April 1970, Cite No. 214-NCC-70-0649. None of this material is contained herein, as such.
7	F	Review and Update Criteria and Standards	11 Modify and Update Existing Standards 12 Modify Criteria	Specific paragraph changes required in KSC-STD-E0012 are defined.
8	All	Summary and Conclusions	All	A summary of the work performed on this program is presented. Emphasis is given to the findings of the on-site effort.
9	All	Recommendations	All	Recommendations for corrective action required to correct the anomalies found during the study effort are contained in this section.
Appendix A		Preliminary Model of Grounding System		This preliminary model is a mathematical model developed with emphasis on performance at high frequencies.
Appendix B		Program for Ground Cable Performance Calculation		This appendix includes a program written in Fortran IV for the calculation of ground cable in conduit. Sample runs are given for standard power cable and welding cable.

VOLUME II - EVOLUTION OF BONDING AND GROUNDING CRITERIA AND ON-SITE EVALUATION OF BONDING AND GROUNDING (Continued)

Section	CIP Task	Title	Proposal Task	Synopsis
Appendix C		Electromagnetic Compatibility Guidelines		A number of guidelines including equations and nomographs for EMC design are included in this appendix for reference.

VOLUME III - BONDING AND GROUNDING PREVENTIVE MAINTENANCE INSTRUCTIONS

Section	CIP Task	Title	Proposal Task	Synopsis
1	G	Introduction Objectives Recommendations	13 Prepare bonding and grounding PMI's	This volume contains a set of routines for preventive maintenance on bonding and grounding details to offset what appears to be the most serious problem at KSC in the area of bonding and grounding.

During the work on this project, Philco-Ford Western Development Laboratories has drawn upon its experience in the area of bonding, grounding, and EMI in the Air Force Satellite Control Facility and other classified ground stations as well as its experience with AGE in the checkout of space vehicles. This experience was invaluable in rapidly identifying specific problem areas at the John F. Kennedy Space Center.

ABBREVIATIONS

Wherever used in this document, the following abbreviations are defined as follows:

A/C	Air Conditioning
ACE	Acceptance Checkout Equipment
AF	Audio Frequency
AFSCF	Air Force Satellite Control Facility
AFSTC	Air Force Satellite Test Center (Sunnyvale, California)
AGCS	Automatic Ground Control Station
ASG	Aerospace Ground
AWG	American Wire Gauge
CDDT	Countdown Demonstration Test
CIF	Central Instrumentation Facility
CKAFS	Cape Kennedy Air Force Station
CURFCOE	Spacecraft Communication and Television Control and Distribution Center in the Manned Spacecraft Operations Building
CW	Continuous Wave
ECS	Environmental Control System
EED	Electroexplosive Device
EGP	Earth Ground Point
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
FRT	Firing Readiness Test
GSE	Ground Support Equipment
IR	Current Reference
IU	Instrument Unit
KSC	Kennedy Space Center
LC-34	Launch Complex 34
LC-37	Launch Complex 37
LCC	Launch Control Center
LEM	Lunar Excursion Module
LH_2	Liquid Hydrogen
LOX	Liquid Oxygen
LUT	Launcher/Umbilical Tower

MCM	Thousand Circular Mils
ML	Mobile Launcher
MMH	Monomethylhydrazine
MSOB	Manned Spacecraft Operations Building
MSS	Mobile Service Structure
NASA	National Aeronautical and Space Agency
NEC	National Electric Code
N_2OH	Nitrous Tetroxide
OIS	Operational Intercommunication System
PMI	Preventive Maintenance Instruction
PTCR	Pad Terminal Connection Room
RF	Radio Frequency
RFI	Radio Frequency Interference
RP-1	Rocket Propellant
SA5	Saturn/Apollo V
S/C	Spacecraft
SCR	Silicon Controlled Rectifier
SHF	Super-high Frequency
S-I-C	Saturn/Apollo V First Stage
S-II	Saturn/Apollo V Second Stage
S-IV-B	Saturn/Apollo V Third Stage
TD's	Technical Distributors
TWT	Traveling Wave Tube
USB	Universal S-Band
VAB	Vehicle Assembly Building
VR	Voltage Reference

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SECTION 1

INTRODUCTION

1.1 BACKGROUND

This volume reports the results of the various tasks which formed the total effort in the development of bonding and grounding criteria for the John F. Kennedy Space Center (KSC), under Contract NAS10-6879. This work is part of a continuing effort by Philco-Ford WDL in this field. The effort began in 1965 with an evaluation and updating of bonding and grounding criteria in the USAF Satellite Control Facility's (AFSCF) remote tracking stations and has extended to various other facilities. Firm standards have been developed and proven valid, and these methods and standards form a baseline for the KSC effort reported herein.

1.2 PURPOSE

The purpose of this volume is to report the results of the individual tasks delineated in Paragraph 1.3 below and, in particular, the on-site evaluation performed on bonding and grounding as implemented at KSC (Figure 1-1). The information developed in these tasks forms the basis for the development of the bonding and grounding criteria in Volume I and the Preventive Maintenance Instructions in Volume III of this report.

1.3 SCOPE

Sections 2 through 6 of this volume cover the work done in the various tasks into which the overall effort was divided. These tasks are as follows:

SECTION	TASK	TITLE
2	A	Review of Bonding and Grounding Methods and Standards
3	B	Evaluation of KSC Bonding and Grounding
4	C	Definition of Hazard Environment
5	D	Definition of Areas Requiring Correction
6	F	Review and Update Criteria and Standards

Other tasks not included herein are as follows:

TASK	
E	Midterm Report (Presented at KSC on 20 March 1970)

TASK	TITLE
G	Preventive Maintenance Instructions (included as Volume III of this report)
H	Preparation of Final Report

Volume I of this report used, as a point of departure, KSC-STD-E-0012, dated 29 December 1969. Changes, additions, or deletions resulting from the work reported in Volume I were then combined with the current issue of the Standard to form a revised Standard.

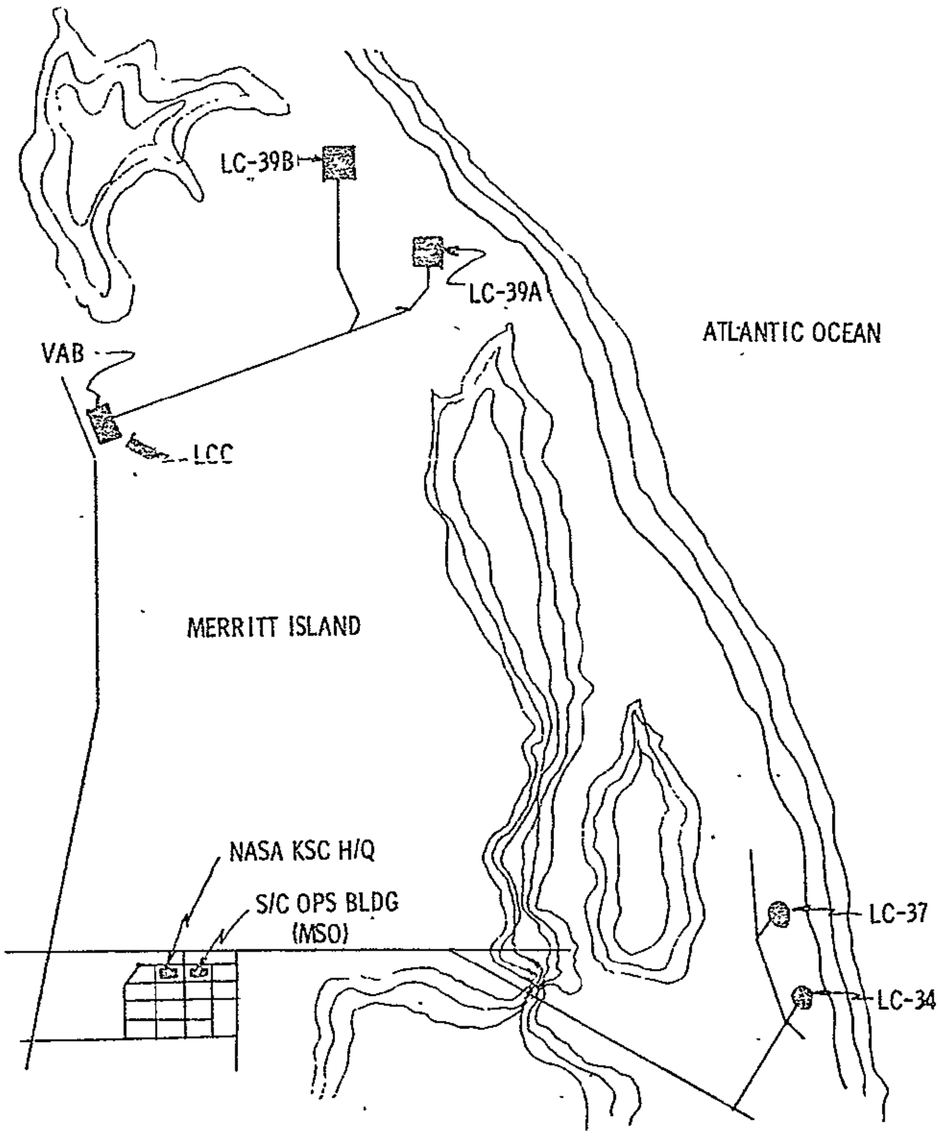

Figure 1-1 Partial Site Plan, Kennedy Space Center

SECTION 2

REVIEW METHODS AND STANDARDS (TASK A)

2.1 GENERAL

2.1.1 Purpose

The purpose of this task was to review existing methods and standards of bonding and grounding in a number of applications and to determine their relevance to the Kennedy Space Center (KSC) problems.

2.1.2 Scope

Sources of existing standards reviewed for this purpose included:

- NASA - Marshall Space Flight Center (MSFC)
- USAF - Air Force Systems Command (AFSC)
- USAF - Satellite Control Facility (SCF)
- Air Force Weapons Lab. (AFWL)
- Stanford Research Institute (SRI)
- Lockheed Missiles and Space Center (LMSC)
- Aerospace Corporation (ASCO)
- Department of Defense (DoD)
- Army Missile Command (USA - AMC)
- National Electrical Code (NEC 1968)
- National Fire Protection Association (NFPA)

The subject matter included electromagnetic interference (EMI), grounding and bonding, lightning protection, and explosion hazard criteria.

2.2 APPROACH

2.2.1 Review

Each of the information sources was reviewed to determine its relevance to the development of grounding and bonding criteria for KSC. Relevance was determined by projecting the problem being approached in the source into the KSC environment to determine if a similar problem existed for which the source offered a solution.

2.2.2 Disposition

Where relevance was found, the information was translated into the KSC criteria in applicable form. Each source item, whether relevant or not, was abstracted on a 4 in x 6 in file card which listed title, author, agency or company, and included a brief abstract of the material contained. Copies of these abstracts are attached.

2.2.3 Review of Abstracts

2.2.3.1 Title: Xenon Lamp Bank, Test Report, TR-918
Author: ---
Agency: JFKSC, NASA, Telemetric System Division

Abstract: This report documents the results of RFI tests conducted on the Xenon Lamp Banks at LC-39A on 7 November 1968. The report includes a discussion of the tests, the conditions under which testing was conducted, the test procedures, the results of the tests, and the conclusions and recommendations resulting from the testing. It points out that all lamps do not radiate and most have a tendency to radiate when set for lower power (usual - 20 kW, lower - 15 and 10 kW). The frequencies of interest are: 259.7 and 296.8 MHz - S/C Comm; 450 MHz - Comd; 503 kHz - IOS; 890 MHz - ODOP; 2106 MHz - USB S/C Comm. The ambient and "lamp on" levels at these frequencies are as follows:

Frequency (MHz)	Ambient	Lamp On	
0.503	60	90	dB/μV/m/MHz
259.7	28	46	
296.8	43	60	
890	75.2	76.2	
450	27.5	29.5	
2105	47	49	dB/μV/m/MHz

2.2.3.2 Title: Internal Voltages and Currents in a Complex Cable Theory and Experiment
Author: E. F. Vance and J. A. Martin
Agency: Stanford Research Institute for AF Weapons Lab

Abstract: This report is a study of techniques for computing the internal voltages and currents produced within cables with solid shields by a surge current flowing on the outer shield. These apply to cables with one or more shields and involve a combination of shielding theory and transmission line theory. Single frequencies were used from 100 Hz to 1 GHz and pulse shield current analysis with 1 ms rise times. The theoretical results were verified by experiment. Imperfections of the cable were studied.

Information in this report is valuable in considering areas of transient voltage interference, as typically noted in the recorders in the LCC.

2.2.3.3 Title: Electrical-Electronic System EMC Test Report for S-1-8, Saturn TR-EE-65-1.
Author: V. E. Haywood
Agency: Chrysler Corporation, New Orleans, La., for NASA

Abstract: EMC test, including radiation and conduction, during post-static checkout of S-1-8 stage of Michoud. Report includes test datum, description of test procedure, conclusions, and recommendations for improvements.

Procedures and data from this report were useful to this effort as a possible guide to recognition of radiated and/or conducted frequencies.

2.2.3.4 Title: Study of Non-Linear Mixing of RF Signals in Steel above 30 MHz
Author: S. Morissette
Agency: IIT Research Institute for NASA-KSC, March 1967

Abstract: Basic research into the mechanism of non-linear signal generation and propagation from metallic mating surfaces. A CW-FM technique for determining the range at which junctions are located is discussed. A list of the most common type of junctions found in service structures is made and modifications suggested. Non-linearity of steel as a function of frequency is investigated experimentally.

This report provided a useful basis for study of effects of re-radiation from non-linear junctions.

2.2.3.5 Title: EMC Principles and Practices, NHB-5320.3
Author: ---
Agency: NASA - Apollo Program, October 1965

Abstract: A manual which documents EMC with the following detailed EMC coverage:

History and Background
Organization
Program Evaluation
Elements of EMI
Theoretical Aspects of Analysis
EMC Characteristics of Electronic Parts
EMC Characteristics of Functional Circuits and Components
Grounding
Bonding
Shielding
Packaging and Equipment Interfacing
Filter Design and Application
Design Considerations for Minimizing Interference
EMI Specifications
Control and Test Plans
Interference Measurements, Test Equipment and Conditions
Susceptibility
Measurement Techniques

This manual contained information in a composite form which aided advance preparation of the many site tasks.

2.2.3.6 Title: Architectural and EMI Guidelines for the Bonneville Power Administration System Control Center C7-1471/030
Author: ---
Agency: North American Aviation, for Bonneville Power Administration, June 1967

Abstract: This report documents the results of a study conducted on architectural designs of a Central Administrative System Control Center to reduce EMI. The report details interference reduction, grounding, equipment power and accessory equipment, bonding, isolation, and shielding, with recommendations for EMI reduction.

This report was useful during the on-site investigation of the EMI in power distribution.

2.2.3.7 Title: Methods of Reducing Transient Overvoltages in Substation Control Cables - #6903
Author: ---
Agency: British Columbia Hydro and Power Authority, June 1969

Abstract: This report describes the results of tests performed to determine the causes, magnitudes, and frequencies of overvoltages and to determine the effectiveness of various preventative and curative measures, such as the use of shielded cable and surge suppression devices. Recommendations are made regarding shielding materials, surge suppression devices in the 500 kV switchyards, secondary problems which may occur in low signal level circuits, and the lines along which the studies should continue.

The information in this report was of value in the investigation of transient phenomena observed in the LCC Firing Room No. 1 during the on-site investigation.

2.2.3.8 Title: Bonding and Grounding Criteria for VAB, LOC TASK 19.4
Author: H. H. Brustle
Agency: G. E. High Voltage Lab, for NASA-KSC, August 1963

Abstract: This report documents the results of a study to assess the adequacy of bonding and grounding criteria planned for construction of the VAB. The degree of protection from lightning, RFI, and shock hazard is recommended.

This report provided the baseline of the Bonding and Grounding philosophy used in constructing the VAB.

2.2.3.9 Title: STC Technical Ground Bus Study
Author: J. C. Carroll
Agency: M. S. C. for AFSCF, January 1967

Abstract: This report is a study to evaluate the effectiveness of the AFSTC technical ground system, to identify sources of conducted noise, and to recommend corrective action for defects. It will be used to develop guidelines for installing any new ground installations.

This report provided an insight into methods of evaluating bonding and grounding at the USAF Satellite Test Center.

2.2.3.10 Title: Lightning Prediction and Protection Techniques, TOR-669(6540)-4
Author: E. B. Arrowsmith
Agency: Aerospace Corporation, for USAF, October 1965

Abstract: This report is an evaluation of surveys of lightning protection at present launch support facilities. It is intended to help determine possible methods of reducing not only damage from lightning strikes, but also the resulting delays in launch schedules. As a basis for the evaluation, information is provided on lightning phenomena, lightning protection devices and systems, instrumentation for detecting and predicting thunderstorm activity, and for measuring and evaluating lightning discharges, as well as an example of a lightning incident at a launch pad. Recommendations are made for improved protection.

This report was used as a basis for studying the lightning ground system used at KSC facility.

2.2.3.11 Title: EMC and Grounding Requirements for Facilities, TOR-1001(2307)-39
Author: J. R. Coge
Agency: Aerospace Corporation, for USAF, March 1967

Abstract: In this document, the general design and test requirements for EMI reduction are defined for reducing the occurrence of these problems in facility structures to a low probability. Some of the areas defined and detailed are:

- Basic Ground Plane - Floating, Single-Point & Multi-Point
- Earth Ground Resistance and Resistivity
- Conductor Characteristics
- System Requirements
  - Bonding of Structures - 50 milliohms
  - Bonding of Support Equipment - 10 milliohms
  - Wire Size Limits - No. 4/0, Short Lengths
- Control and Computer Rooms
  - Lightning Ground
  - Isolation of Tech, Power, and Facility Grounds

- Shielding - AF and RF
- Counterpoises
- Filters - -80 dBm minimum
- Mobile Equipment - see MIL-STD-826
- Power Regulation
- Cable Routing

Testing

This document was useful as a basic reference for an established ground philosophy which was useful as a guide for evaluation during the on-site investigation.

2.2.3.12 Title: Technical Spec. for LC-39, LUT's 1, 2, and 3, LOC-39-001
Author: ---
Agency: NASA-LOC, KSC, Rev. April 1965

Abstract: Detailed construction spec for the LUT's, from structural steel to nuts and bolts.

This specification was a valuable general guide to the LUT's construction.

2.2.3.13 Title: Technical Spec for Mechanical and Electrical Installation of LUT's 1, 2, and 3, LOC-39-002
Author: ---
Agency: NASA-LOC, KSC, Rev. April 1965

Abstract: Detailed requirements for installing all electrical and mechanical equipment for support of vehicle, operation of LUT, and safety of personnel.

This specification was valuable in providing familiarization with the electrical construction and installation details of the LUT's.

2.2.3.14 Title: MIL-STD-461A, EMI Characteristics, Requirements for Equipment
Author: ---
Agency: Department of Defense, August 1968

Abstract: Detailed requirements and test limits for the measurement and determination of the EMI characteristics of electronic, electrical, and electromechanical equipment. These requirements are for DoD procurements as specified in individual equipment specification, contract, or order.

Definition of test requirements and methods are included and intended for design of equipment. Intended to be used with MIL-STD-462 and -463.

This standard was a valuable reference guide for the on-site investigation in the EMI areas.

2.2.3.15 Title: MIL-STD-462, Measurement of EMI Characteristics
Author: ---
Agency: Department of Defense, August 1968

Abstract: This standard establishes techniques to be used for the measurement and determination of the EMI characteristics of electronic, electrical, and electromechanical equipment, as required by MIL-STD-461A and defined in MIL-STD-463.

This standard supplements 461A with detailed descriptions of measurements and tests.

2.2.3.16 Title: MIL-STD-463, Definitions and System of Units, EMI Technology
Author: ---
Agency: Department of Defense, June 1966

Abstract: EMI symbols, physical quantities, definitions, and terminology used in MIL-STD-461 and -462. Used as the basis of definitions, this standard provides, among others, the following pertinent definitions:

Grounding - Connecting a metal member or bonded member to the nearest structural steel which is bonded to the Ground Plane.

Bonding - The joining or connecting of separate pieces of metal.

2.2.3.17 Title: MIL-B-5087B, Bonding, Electrical, and Lightning Protection for Aerospace Systems
Author: ---
Agency: Department of Defense, February 1968

Abstract: This specification covers the characteristics, application, and testing of bonds. Areas of concern are:

Hardware use allowable, clamps, jumpers
Classification of bonds and limits
Current-carrying capacity of wires and cables in or out of conduit
Voltage drops tolerable
Bolting installation and insulation, corrosion prevention
Lightning protection zone -60°.

This specification supports AFCO TOR-669 (6540)-4 (Paragraph 2.2.10) and the NEC in considerations of lightning damage protection. It was valuable in preparation for on-site evaluation and review of KSC standards.

2.2.3.18 Title: MIL-STD-285, Attenuation Measurements for Enclosures, Electromagnetic Shielding, for Electronic Test Purposes, Method of
Author: ---
Agency: Department of Defense, June 1956

Abstract: This specification covers a method of measuring attenuation characteristics of enclosures from 100 kHz to 10 GHz. Includes definitions of terms.

This standard is very general and basic and a good source of measurement guidelines.

2.2.3.19 Title: MIL-STD-826A, EMI Test Requirements and Test Methods
Author: ---
Agency: Department of Defense, October 1967

Abstract: This standard covers explanation of terms, report format, limits, and uniform test methods for testing equipment, systems, and subsystems to their EMI, and susceptibility characteristics.

SUPERSEDED BY MIL-STD-461A

2.2.3.20 Title: MIL-STD-704A, Electric Power, Aircraft, Characteristics and Utilization of
Author: ---
Agency: Department of Defense, August 1966

Abstract: Definitions of terms used, categories of equipment, and requirements. Of interest are paragraphs:

5.1.3.6 Modulation (of AC)
5.2.3 Transient Voltage (of AC)
6.7 Voltage Transients
6.8.1 Self-Modulation - Limit of modulation by a varying load
6.9.3 Phase Balance
Figures 1 to 17.

Conditions and limits from this standard were useful in recognizing ac power problems at the rack level.

2.2.3.21 Title: MIL-E-6051D, EMC Requirements, System
Author: ---
Agency: Department of Defense, July 1968

Abstract: General EMC Specification
Covers: EMC Program (EMCP)
System Requirements

Criticality Categories:
Grounding
Lightning Protection
Control Plan Details

This specification generally supports MIL-B-5087B, but with more emphasis on personnel protection from current surges.

2.2.3.22 Title: MSFC-SPEC-279, EMC
Author: ---
Agency: NASA-MSFC, June 1964

Abstract: Detailed criteria for EMC testing system and subsystems for interference and susceptibility. Simulation and test procedure are stressed.

Although this specification refers to MIL Standards 461A, 462, and 463, specific test setups and examples are stressed.

2.2.3.23 Title: National Electrical Code No. 70, 1968
Author: National Fire Protection Association
Agency: United States of America Standards Institute

Abstract: Specific minimum safety requirements for all structures. Of specific interest are:

Article 250	-	Grounding
Article 280	-	Lightning Arrestors
Article 300	-	Wiring Methods
Article 310	-	Conductor Rating
Article 500	-	Hazardous Locations
Article 513	-	Aircraft Hangars
Article 800	-	Communication Circuits
Chapter 9	-	Tables

2.2.3.24 Title: KSC-STD-140A, Bonding and Ground Standard
Author: ---
Agency: NASA, KSC, June 1966

Abstract: This standard provides a uniform determination of the requirements for bonding and grounding of facilities and ground support equipment at KSC.

Specifics are:

Definitions - Earth, Ground, Bonds, Internal and External, Corrosion, etc.
Requirements - Bonding, Grounding, Materials and Maintenance, Zone Definition
Lightning ground system requirements refer heavily to KSC-23-16, Policy for Lightning Protection, NASW-410-20-12-22 and NASW-410, Task 4.2.3.3.

SUPERSEDED BY KSC-STD-E-0012, DATED 29 DECEMBER 1969

2.2.3.25 Title: DTI-E-9, Terminating and Grounding Shields in LF Instrumentation Cables
Author: ---
Agency: NASA-KSC, March 1969

Abstract: This standard is for design of low frequency instrumentation cables, shield termination, and grounding. Specifics for types of cables and connectors are given.

2.2.3.26 Title: Techniques and Devices for the Protection of Electrical and Electronic Systems from Lightning Transients
Author: R. E. Buies and F. A. Fisher
Agency: High Voltage Lab of GE Co. for USAF - Kirkland AFB, June 1963

Abstract: This report describes protection from lightning effects for electronic systems by:

a. Discussing lightning characteristics
b. Defining specific protection techniques for an equipment experiencing a direct stroke, with different equipment grounding configurations
c. Discussing different surge protection devices with data showing their limits and applicable usefulness
d. Discussing application of protection technique devices with system design, grounding design, and protective device used in relation to circuit characteristics
e. Summarizing and recommendations.

2.2.3.27 Title: Prevention, Detection, and Suppression of Hydrogen Explosions in Aerospace Vehicles
Author: G. J. Caras
Agency: USA-AMC, NASA-MSFC, March 1966

Abstract: This study is a comparison of data and research from test results of various variables in H_2 versus O_2 concentrations to see to what degree an explosion can result. Comparisons with propane mixtures are also used. Different types of detonators were used and quenching distances are detailed. Grounding influence on ignition is emphasized.

This paper was a primary reference in the investigation of explosion hazards in Task C.

2.2.3.28 Title: Earth Conduction Effects in Transmission Systems
Author: E. D. Sunde
Agency: D. Van Nostrand Book Co. for Bell Telephone Labs

Abstract: This volume is primarily concerned with fundamental methods in the analysis of earth conduction effects and basic principles underlying protective measures against resultant circuit disturbances. This book provides the basic theoretical concepts for an analysis of grounding systems.

2.2.3.29 Title: Lightning Protection for Saturn Launch Complex 39 NASW-410-20-13-22, September 1963
Author: ---
Agency: High Voltage Lab., G. E. Co., for NASA-KSC

Abstract: This report contains the results of a study of the effects of lightning on Launch Complex 39. The study contains theory, investigations, and calculations as well as specific constructional recommendations for reduction and control of lightning at LC-39.

2.2.3.30 Title: Analysis of Lightning Effects on Launch Complexes 34 and 37, NASW-410, Task 4.2.3.3, July 1964
Author: ---
Agency: High Voltage Labs., G. E. Co., for NASA-KSC

Abstract: This report gives the results of an investigation to determine the effects of lightning strokes on LC-34 and LC-37, with recommendations for techniques to reduce the potential hazard from lightning.

SECTION 3

EVALUATION OF KSC BONDING AND GROUNDING (TASK B)

3.1 GENERAL

3.1.1 Purpose

The purpose of this section is to report the results of the on-site evaluation effort carried out at the John F. Kennedy Space Center as Task B of the work under Contract NAS10-6879, Development of Bonding and Grounding Criteria.

3.1.2 Scope

In accordance with customer direction, this evaluation effort was conducted in Launch Complexes 39, 34, and 37 and in the Manned Spacecraft Operations Building at KSC and Cape Kennedy Air Force Station (CKAFS). It included physical inspection, measurement of ground resistivity and ground resistance of earth ground points and measurement of noise in the time and frequency domains at selected points. Where relevant, special tests were made to determine the cause of acknowledged anomalies and their remedy.

3.1.3 Reference Documents

The following documents and drawings were a part of the inputs for the performance of this task:

GP-679	KSC - LC-39 Facilities Space Control Document
77K04158	KSC - Grounding Systems Installation, LC-34
77M1270	KSC - Cable Installations - LUT LC-39
77K04150	KSC - Facilities Grounding - VAB
203-382	KSC - Installation and Communication Cable for LC-39
--	KSC - Grounding Plan - MSO Building
--	KSC - Grounding Plan - LC-39, LCC

3.2 INSPECTION PHASE

3.2.1 Introduction

The purpose of the inspection phase was to determine the condition of the various parts of the grounding system on the basis of criteria developed in the past throughout the AFSCF. The inspection was supported by photographs which show how a particular facet of the system was implemented or how anomalies were found. This section summarizes the findings of this inspection.

3.2.2 Launch Complex 39

The grounding aspects of the major components of Launch Complex (LC) 39 were inspected insofar as access was available. During the inspection, Apollo 13 was in countdown for the Firing Readiness Test (FRT) and the Countdown Demonstration Test (CDDT), and some areas and entities were under integrity seal and could not be inspected. However, it is estimated that 90% of the entire complex was covered during the inspection.

3.2.2.1 Vehicle Assembly Building

3.2.2.1.1 Grounding Systems, Vehicle Assembly Building. The Vehicle Assembly Building (VAB), where the Saturn V vehicles are completely assembled and partially checked out, consists of four high-bays in which the entire 365-foot vehicle may be assembled, six low-bay cells in which the individual stages (except the S-I-C) are readied for assembly into the vehicle and six towers (designated A to F) 41 stories high. The majority of the intermediate floors contain offices, laboratories, and checkout equipment facilities. In each of the towers, distribution of instrumentation ground (I-Ground) to using locations is generally accomplished by #4/0 AWG insulated stranded copper cable installed in aluminum or ferrous conduit. Risers are installed through the electrical closets on each floor. At each floor, where required, a tap is made to the riser and is fed to the point of use, where it is terminated on an I-plate mounted on 5-inch insulators.

A separate counterpoise for each tower is located at some distance from the building. This counterpoise consists of three 50-foot copperweld ground rods placed on a 50-foot equilateral triangle. The rods are bonded together along all three legs of the triangle by #4/0 AWG cable. For each tower, a cable enters near the edge of the high-bay doors (see Figure 3-1) and is fed in conduit to the riser location near the transfer aisle - a direct distance of 192 feet. The equipment ground (E-Ground) is carried entirely by the building steel. The columns of the building are carried on 150-foot, 16-inch diameter steel pilings which rest on limestone bedrock. The columns and their pilings are electrically bonded together by #4/0 AWG copper cable exothermally welded to the steel. Figure 3-2 illustrates a welded bonding connection to a structural support column. This forms an impressive contact with the earth not only because of the mass of steel involved, but also because of the low resistivity of the soil below 32 feet (resulting from the seepage of salt water from the ocean four miles away). Where E-Ground is required, E-plates are welded to the building steel or are connected by a cable to the nearest steel. Figure 3-3 shows a typical E-plate installed correctly.

3.2.2.1.2 Grounding Anomalies, VAB Tower A. Tower A was inspected in detail and the following anomalies were discovered:

- The cable from the ground point to the riser in Room 1A3 is #4/0 AWG. The cross-sectional area of #4/0 AWG is 216,000 circular mils (cmil). The rule of thumb of 2000 cmil per running foot (i.e., 4.7 milliohms total resistance) calls for at least 384,000 cmil for the distance of this run.

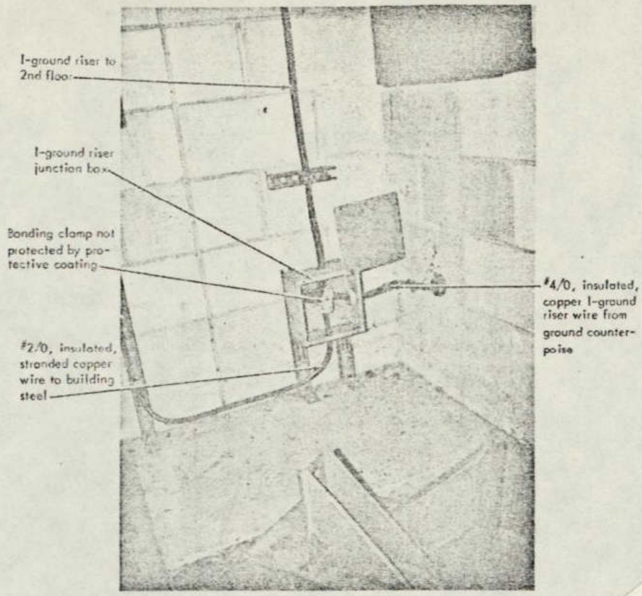

Figure 3-1 I-Ground Riser from Ground Counterpoise in Tower A of VAB. Gutter tap was found to be loose.

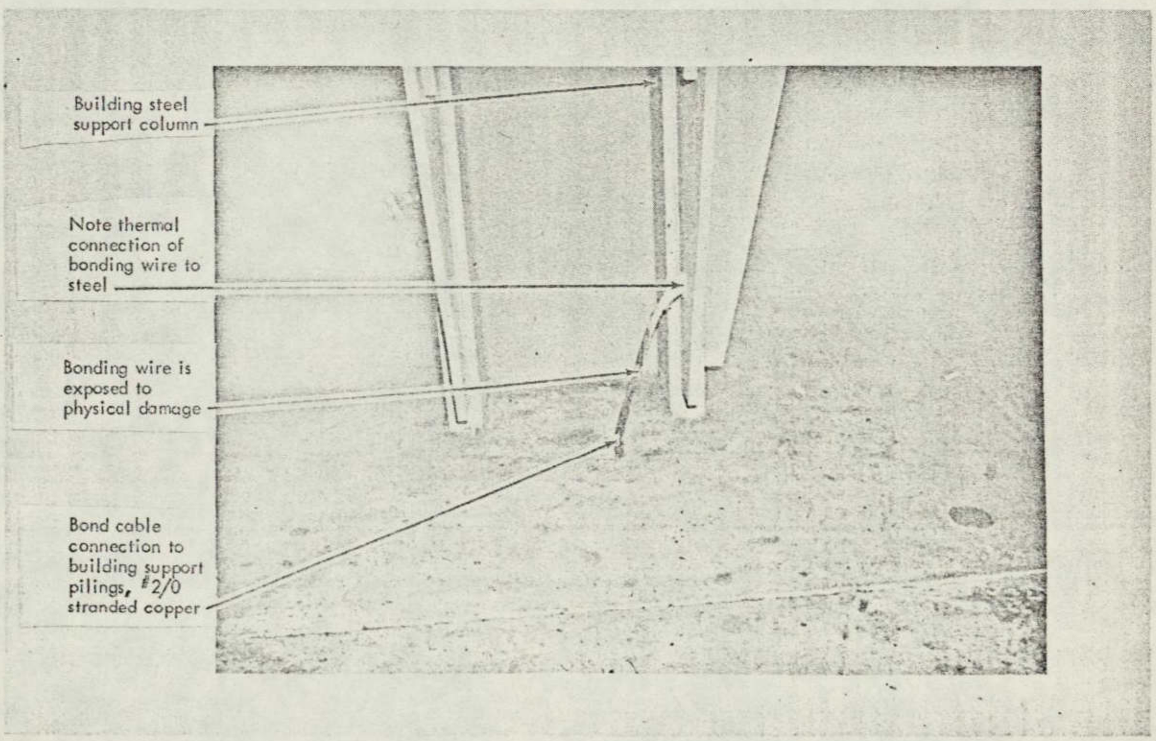

Figure 3-2 Typical VAB Structural Steel Ground. 2/0 AWG cables connect to Earth Grounding Counterpoise.

- The separate instrumentation ground system for this tower is connected to building steel in Room 1A3, through a #2/0 insulated copper wire.

- No conduit has been provided for the riser between the first and second floors. Figure 3-4 shows the exposed wire. This riser is adjacent to a high H-field source (transformer banks in an adjacent room) and may be subject to induced currents.

- Conduit is provided from Rooms 3A3 to 31A3, but the riser cable is missing between Rooms 3A3 and 6A3. The end of the riser cable to the 31st floor is lying on the floor of Room 6A3 as shown in Figure 3-5.

- The I-Ground feeder to Platform A from the 31st floor should be shielded, ideally.

- Although an open circuit should exist between the E- and I-plates on Platform A (because of the missing riser between Floors 3 and 6), a resistance of 0.022 ohm was measured between them using both a Wheatstone and Kelvin bridge. Time did not permit further attempts to isolate this compromise.

3.2.2.1.3 Grounding Anomalies, VAB Tower B. Anomalies found in Tower B include the following:

- The same comment applies on the gauge of the riser feeder as that made in Tower A.

- The I-Ground system is connected to building steel in Room 1B3 in the same manner as in Room 1A3.

- In Room 15B12, a #12 AWG wire is used to distribute the I-Ground from its plate to 12 I-Ground points around the room. Based on the rule of thumb of 2000 cmil per running foot, #12 AWG is adequate for three feet only.

- Room 15B13 used a similar application of #12 AWG wire. In addition, a #4/0 AWG cable was attached to the I-plate and run for eight feet in conduit to a 12-inch open cable tray. It then ran 60 feet back to Room 15B2 (which contains the I-riser) and through the wall into Room 15B1A. This room was locked and is understood to be the OIS (Operational Intercommunication System) Distribution Center for the tower.

- On the 16th floor, a refrigerator was in intermittent contact with the I-plate. There were other cases of furniture in contact with I-plates.

- In Rooms 24B18 and 25B15, the I-Ground branch cable was looped at the end of the conduit. The plate has apparently been removed.

3.2.2.1.4 Grounding Anomalies, VAB Tower C. Tower C has 13 full floors and 9 partial floors installed. Many of the full floors are merely slabs with wire fence. Accordingly, the I-Ground system is not extensive. In Room 1C1, the I-Ground

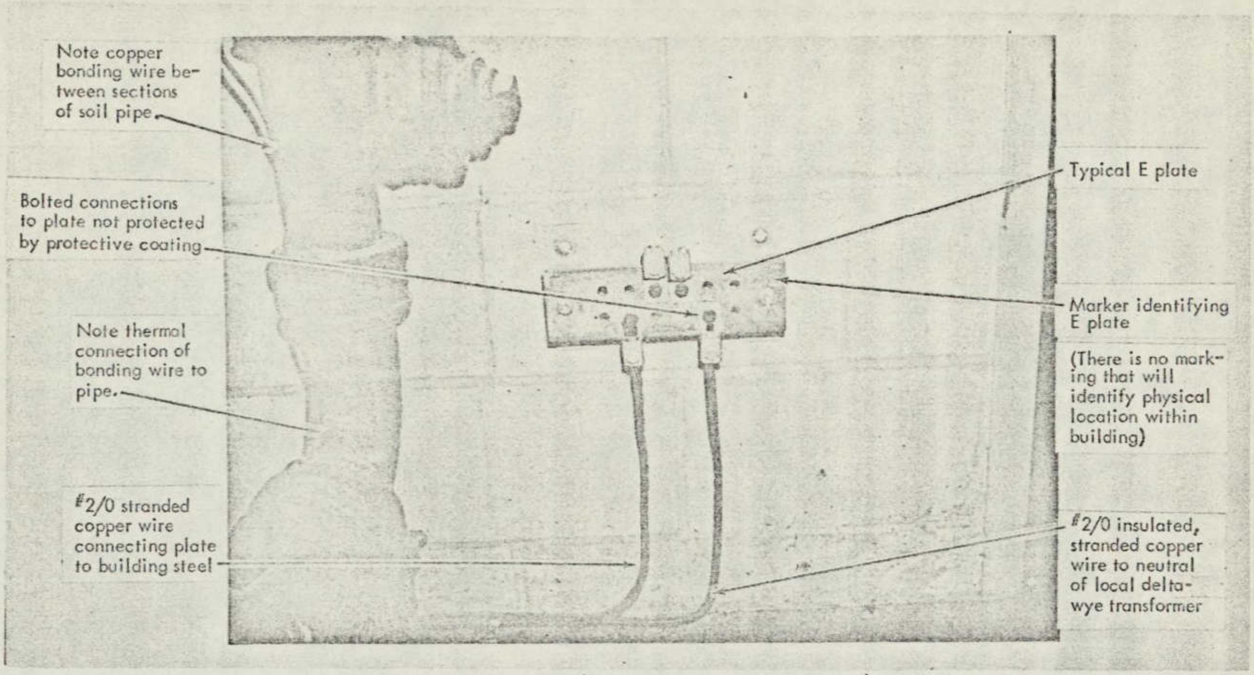

Figure 3-3 Typical E-Plate in High-Bay/VAB. Note bonding used between leaded sections of soil pipe.

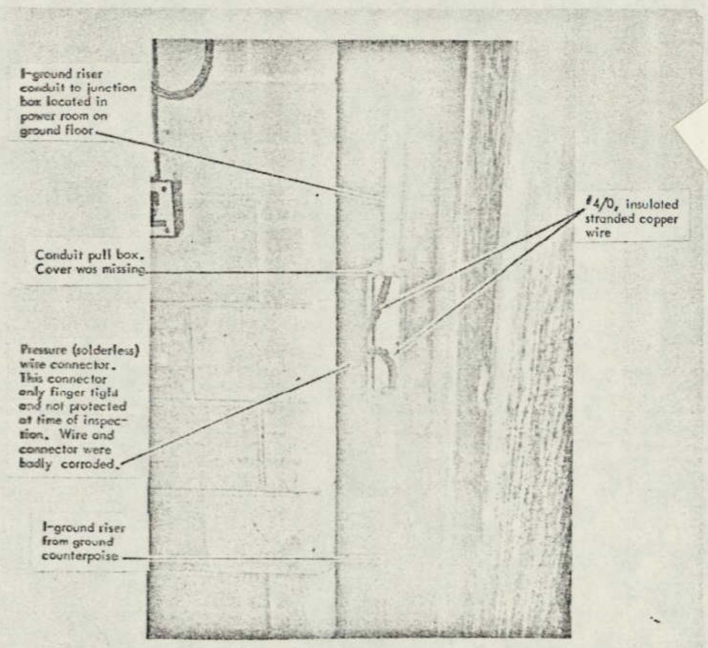

Figure 3-4 I-Ground Riser, Room 1A3, VAB. 4/0 AWG wire at right of box is from counterpoise. 2/0 AWG connects to 2nd-floor joint of structural steel. Note lack of conduit.

riser is connected to building steel. There has been no utilization of the I-Ground counterpoise. There are no branch circuits taken from the riser.

3.2.2.1.5 Grounding Anomalies, Tower D. Grounding anomalies found in Tower D include the following:

- I-Ground riser is tied to building steel in Room 1D3 through a surge protector.

- Room 5D5 had a bare #1/0 AWG cable extended in conduit from the I-plate to cable trays and racks. The I-Ground riser was compromised by the conduit and the extension of the cable rack.

3.2.2.1.6 Grounding Anomalies, Tower E. Tower E, which is currently the most active tower, contained a number of anomalies. These are detailed as follows:

- As in Tower D, I-Ground riser was tied to building steel through a lightning surge protector. Figure 3-6 shows the installation.

- Room 1E21 is a screen room used for microwave testing. An I-Ground branch cable or ground point feeder (it could not be determined which) was fed into this room through an RFI-type filter and out through another filter.

- Risers have mixed treatment. Some are enclosed in ferrous conduit and in aluminum conduit, and many inter-floor sections have no conduit. In general, treatment of risers and branches is not consistent in this tower.

- In Room 26E7, several compromises of I-Ground exist. I-Ground is distributed to the equipment racks through a three-inch copper pipe ground lead which runs over the top of the racks. Connection is made to individual racks using bare copper straps. Waveguide coming from equipment in those racks is bonded to building steel. The electrical conduit feeding the racks was observed to be rather warm during operation of the racks. Further investigation revealed that 12 breaker circuits were served by only four neutral lines of the same gauge (#12 AWG).

3.2.2.1.7 Grounding Anomalies, Tower F. The grounding arrangements in Tower F were almost identical with those in Tower C, except that risers were provided to serve the movable platforms for the high bay. Connection was made to building steel at the first floor level. A feeder was also provided to the counterpoise.

3.2.2.1.8 Grounding Anomalies, Roof. The principal area of concern for grounding on the roof is the treatment of the air terminals. The following anomalies were found:

- The majority of the air terminals were fabricated of aluminum and were attached to steel railings with U-bolts, forming a bimetallic junction.

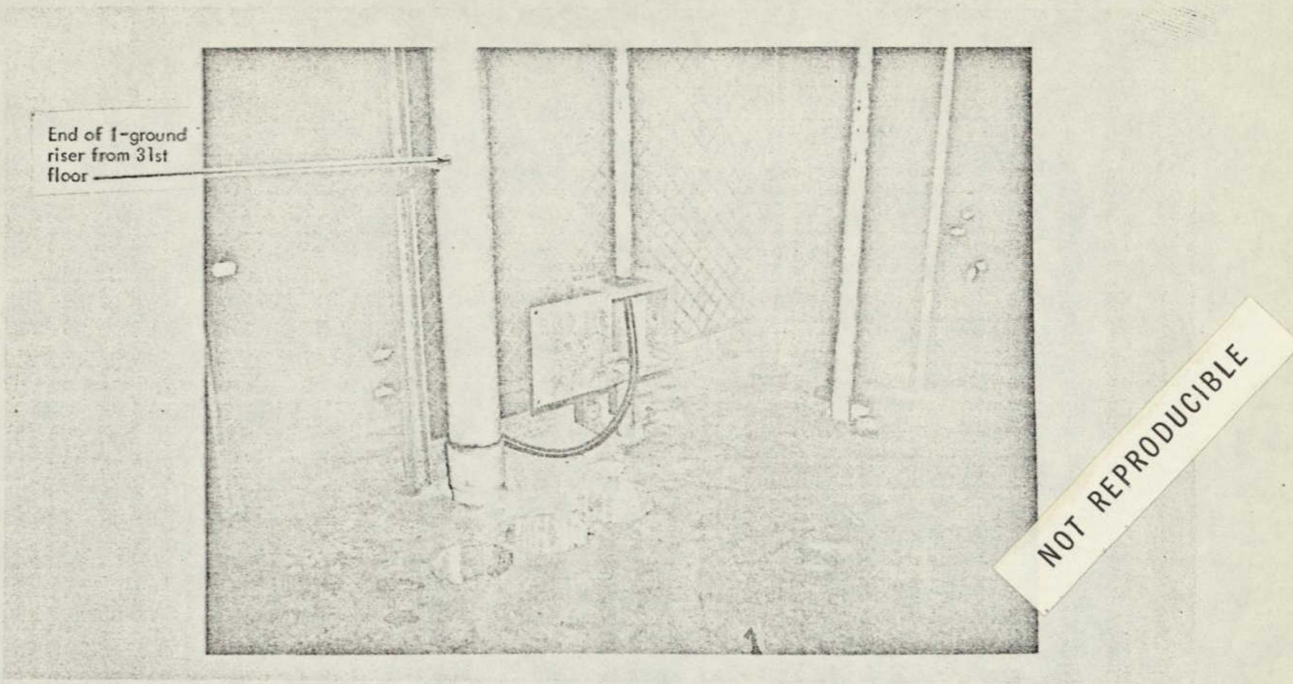

Figure 3-5 VAB, Tower A, Room 6A3 - Bottom End of I-Ground Riser. No connection to I-ground.

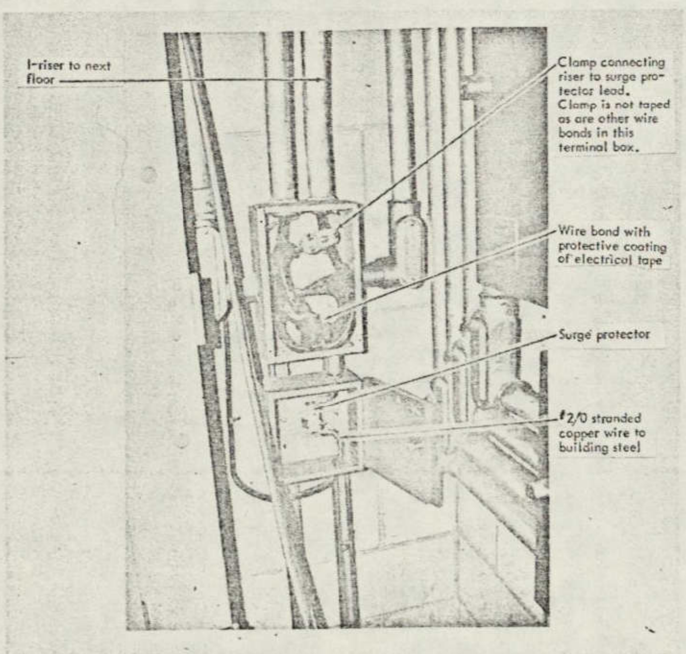

Figure 3-6 VAB, Tower E, Room 1E3 - I-Ground Riser Connections. Note surge supressor connected to structural steel.

- One section of cable tray was found to be high enough above the roof that it was marginally outside the cone of protection of any nearby air terminals.

- One parabolic antenna reflector had its air terminal broken. It is understood that this antenna is not in use.

3.2.2.2 Launch Control Complex

3.2.2.2.1 General. The Launch Control Complex (LCC) building is located adjacent to the VAB. It contains the firing rooms for executing and controlling the launch of the Saturn V/Apollo vehicle, together with the associated electronics. There are four firing rooms. Firing Rooms 1 and 2 are the only ones currently in use. Firing Room 3 is down moded and Firing Room 4 was never implemented and is currently used as a briefing room. The LCC is a four-story building with the firing rooms on the third floor. Auxiliary equipment is installed on the second floor, and the first floor contains the communications complex, office areas, and a cafeteria. The fourth floor contains offices and the upper portion of the firing rooms.

3.2.2.2.2 Grounding System. Two earth ground point systems are provided for this building: the E-Ground and the I-Ground systems. The E-Ground system consists of a series of ground rods placed at intervals of 50 feet around the perimeter of the building and interconnected by a bare #4/0 AWG cable. The ends of this cable terminate on an E-plate in Room 1P7. The I-Ground system consists of three 50-foot rods placed in a 50-foot equilateral triangle about 100 feet to the rear of the building. These rods are interconnected with a #4/0 AWG cable and a cable is provided from this triad to an I-plate in Room 1P7. Risers for both the I- and E-grounding systems are installed to feed the second through fourth floors in the P half of the building. Feeders are provided to Room 1P9, the communications center, and Room 1R9, where risers are provided for Floors 2, 3, and 4 for the second half of the building. An additional grounding system is provided for the ACE system. This is derived from the E-plate in Room 1P7 and consists of a "SIGNAL" ground and "STATIC" ground, corresponding to I- and E-grounds, respectively. These two grounds are implemented with 3-inch copper pipe and are isolated from any contact with building steel or other grounds. These grounds are distributed to using points on the second floor and to the firing rooms on the third floor.

3.2.2.2.3 LCC Grounding Anomalies. Grounding anomalies noted during the inspection of the LCC include the following:

- Ground connections to many of the racks and consoles were made by bolting a terminal lug to an anodized portion of the rack or console framework. This results in a connection of doubtful integrity since the anodize process results in a high-resistance surface. Figure 3-7 illustrates such a connection.

- In Room 2P10, equipment racks were connected to SIGNAL ground, yet no insulating pad was placed between the rack and the raised floor sections to prevent a compromise.

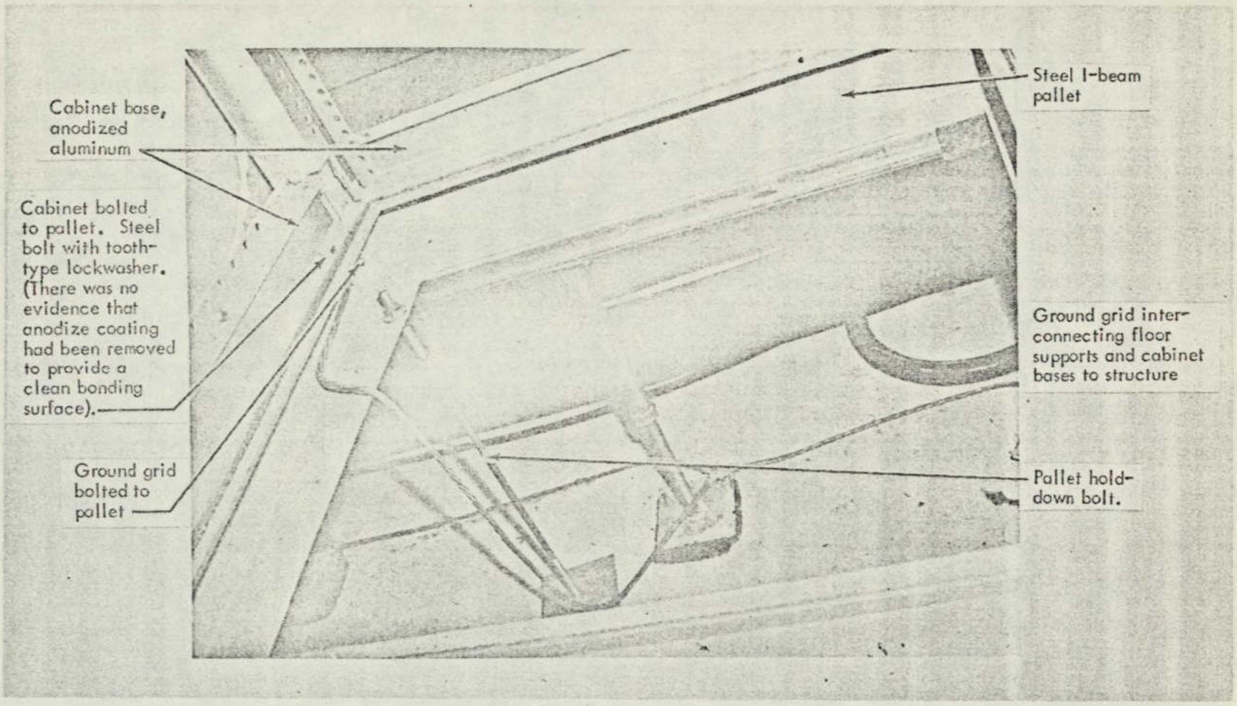

Figure 3-7 LCC Firing Room 3 - Utilization of Facility Ground. Note connections to raised floor and enclosures.

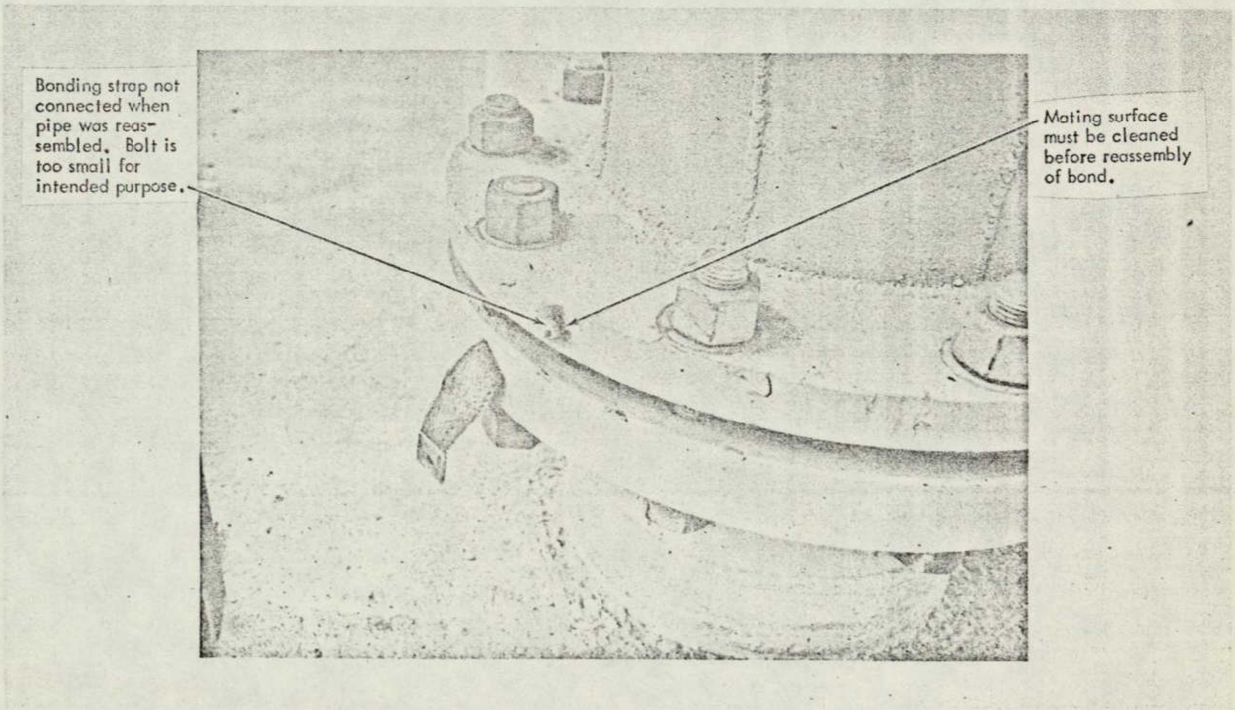

Figure 3-8 LC-39, Pad B - Disconnected Strap. Note inadequate size of screw for strap.

- The "green wire" ground connection used in conjunction with the ac power system was extended from the chassis served by the associated feeder to a ground connection in the power distribution panel. It was reported, but not verified, that the connection was actually made to the neutral in at least some of the power panels.

- I-Ground was compromised by a direct connection to the E-Ground riser in Room 1R9.

3.2.2.3 Pads 39A and 39B

3.2.2.3.1 General. These two pads are, for this purpose, identical. They include six adjustable columns on which the Launcher/Umbilical Tower and Mobile Service Structure are placed, the floor trench, the ECS and PTCR Building and the various service buildings and structures. The gounding system is extensive and consists of many rods around the periphery of the pad, all interconnected with large gauge cable and distributed to using points. The only anomalies found on inspection were those resulting from lack of proper maintenance. These included frayed or broken straps or cables (Figure 3-8), corroded terminals (Figure 3-9), loose pipe bond straps, and painted contact surfaces. Figure 3-10 is an illustration of good bonding practice for pipes. The arrangement of the gounding point for the hypergolic service cart (Figure 3-11) could be more effectively designed; the present design leads to the creation of a "rat's nest" of cables which could be hazardous to anyone walking in the area.

3.2.2.4 Launcher/Umbilical Tower (LUT)

3.2.2.4.1 General. The Launcher/Umbilical Towers (LUT's) are designed for the assembly, servicing, checkout, and launch of the Saturn V/Apollo vehicle. The vehicle is assembled and partially checked out on the LUT while in one of the high-bay areas of the VAB. When assembly and preliminary checkout are complete, the entire package (LUT with Saturn V/Apollo) (weight - 17,000,000 pounds) is moved to the launch pad on a crawler-transporter. After placement of the LUT in position on the pad, a Mobile Service Structure (MSS) is moved into place adjacent to the LUT. The MSS has a number of movable platforms which duplicate those in the VAB to provide access to critical portions of the vehicle and to provide environmental protection during the period up to servicing.

3.2.2.4.2 LUT Grounding System. The LUT is provided with both an E- and I-grounding system which originate at a common point. The common point is a copper plate located near the ceiling of Room 3AB shown in Figure 3-12. This plate is properly brazed to the steel structure and has five cables attached to it. These cables are defined as follows:

- 500 MCM to ground terminal on outside of LUT (Side 2) for connection to terminal on Column 5 of the support structure

- 500 MCM to TD9074 for spacecraft circuits

- 500 MCM to TD9073 for launch vehicle circuits

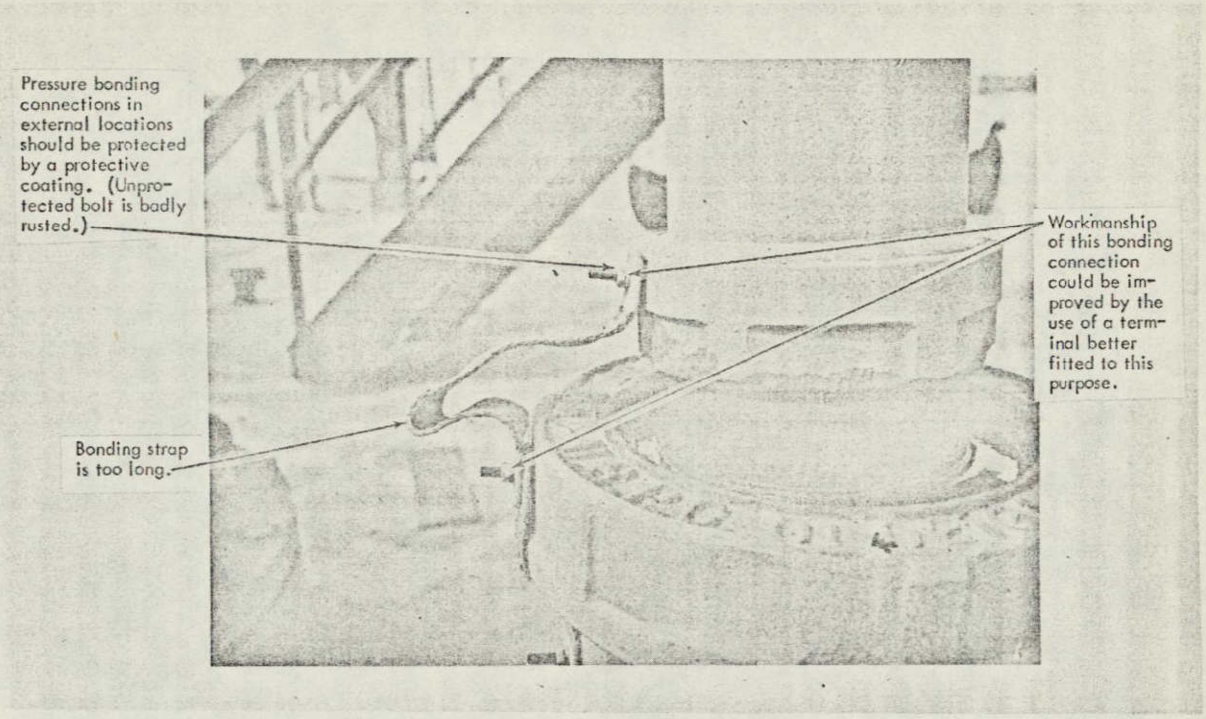

Figure 3-9 LC-39, Pad B - Bonding on LUT Support Leg. Note corrosion of screws and inadequate size of screws.

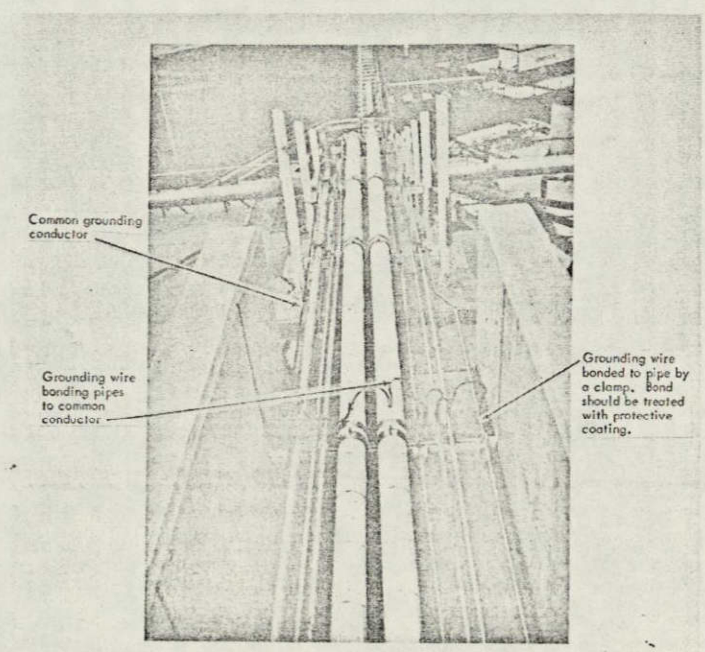

Figure 3-10 LC-39, Pad B - Typical Bonding of Service Lines

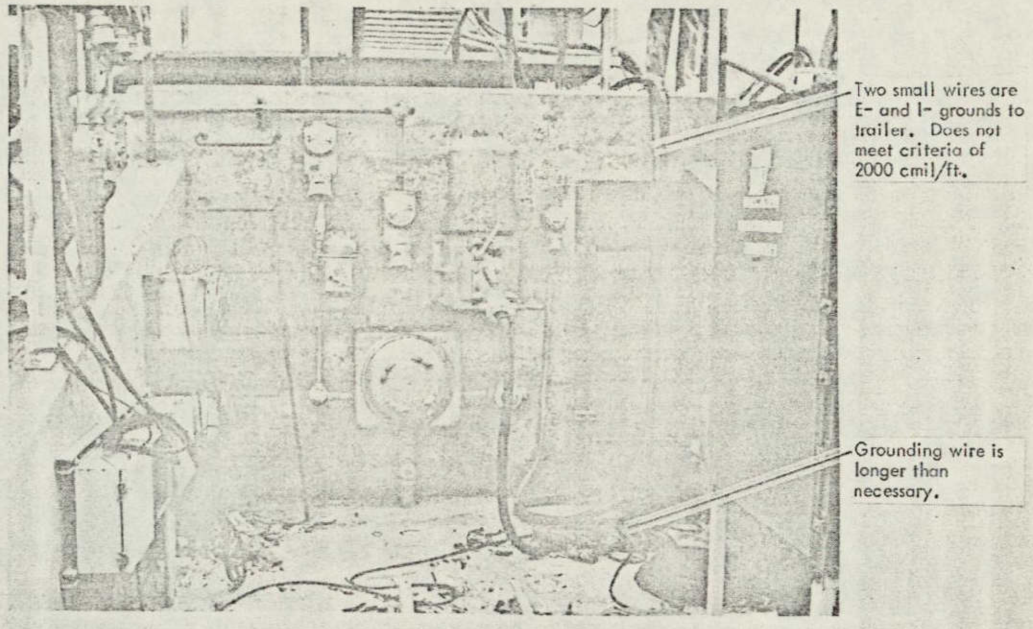

Figure 3-11 LC-39, Pad B - Connecting Pit Adjacent to N_2O_4 Trailer. E-ground box is at left and I-ground behind TD on right. Note coiled I-ground lead and random lay of E-ground cable.

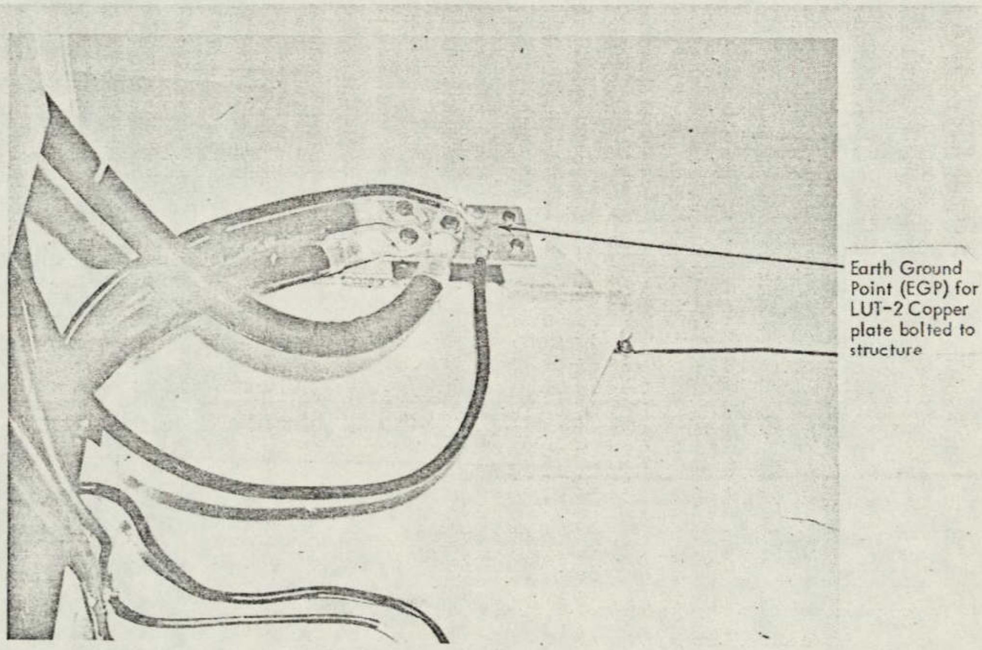

Figure 3-12 LUT-2 Single-Point EGP, Room 3AB. 500 MCM cables are to TD 9029, TD 9073, and external ground point. 2/0 AWG cables are to hold down arms I and III.

- 2/0 to Hold-down Arm I (Vehicle Ground)

- 2/0 to Hold-down Arm III (Vehicle Ground)

E-Ground is distributed throughout the LUT using the welded steel framework as a medium. I-Ground is distributed from the two technical distributors (TD's) cited above to the using points. Some of the I-Ground distribution cable is shielded (shield connected to E-Ground). The ground connection is made directly from a TD or from an I-plate which may be fed from TD9074, TD9073, or a TD on the level involved. The ACE room on Level 280, for example, has I-plates fed by two #4/0 cables in a single shield. These two cables originate in TD9029 on that level. The TD9029 is in turn connected to TD9074. The total distribution of the I-Ground system becomes complex because some ground leads are designated for use as 28-volt ground returns and others for signal grounding.

3.2.2.4.3 LUT Bonding and Grounding Anomalies. The following anomalies were found in the inspection of the three LUT's:

- The 500 MCM cable interconnecting the common ground point in Room 3AB and the outside ground connection parallel within an inch one side of a three-phase delta primary power circuit for approximately 60 feet. The mutual inductance between these two cables for this length is 4.8 microhenries. The capacity between them is approximately 60 picofarads. This means that every transient in the power system will be superimposed on the common reference point. The high frequency impedance of the shunting path through the LUT framework is not low enough to offset this effect.

- Each LUT had a few anomalies resulting from improper maintenance. Figure 3-13 shows improper installation of a temporary grounding wire at Pad A.

- A number of compromises exist between E- and I-grounds. For example, in the ACE room on the 280-foot level, chassis and logic grounds (E and I, respectively) are connected at C14-267-1, one of the portable ACE units.

- On the 80-foot level, Units S14-121B and 14-053 have their E-1 and E-2 (E and I) grounds compromised internally.

- In the ACE Room (280-foot level), the portable units are set on an equipment shelf and some equipments depend on this contact for E-Ground. On two units observed, E-1 terminals were provided but not used. Figure 3-14 shows a typical equipment shelf and E-Ground in the ACE Room of LUT 1. The E-cable is unduly long.

- A relatively high impedance was found between the ACE Room and the LUT structure where the room was not bonded to the structure, see Figure 3-15. This has been corrected on LUT 3 by installing welded bond straps. See Figure 3-16. It is understood that this is to be done on LUT's 1 and 2 also.

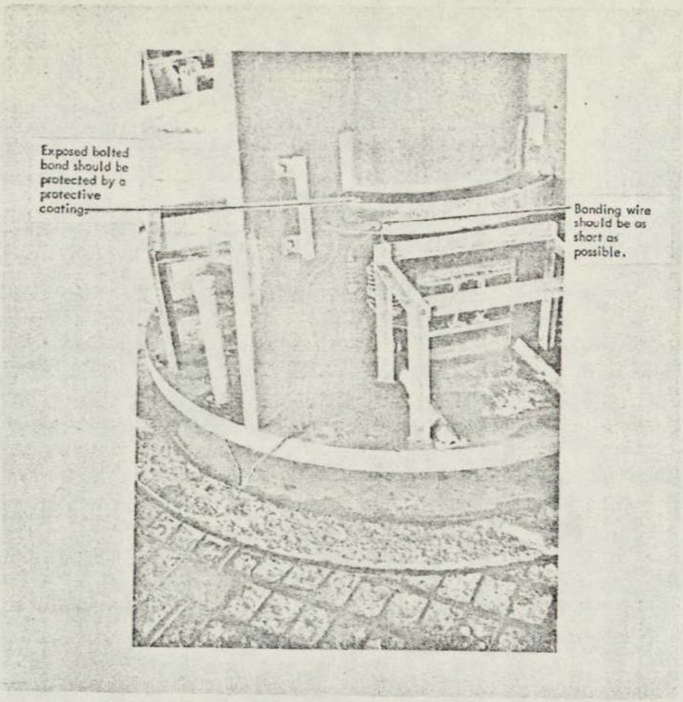

Figure 3-13 LC-39, Pad A - Grounding for Shock Absorber

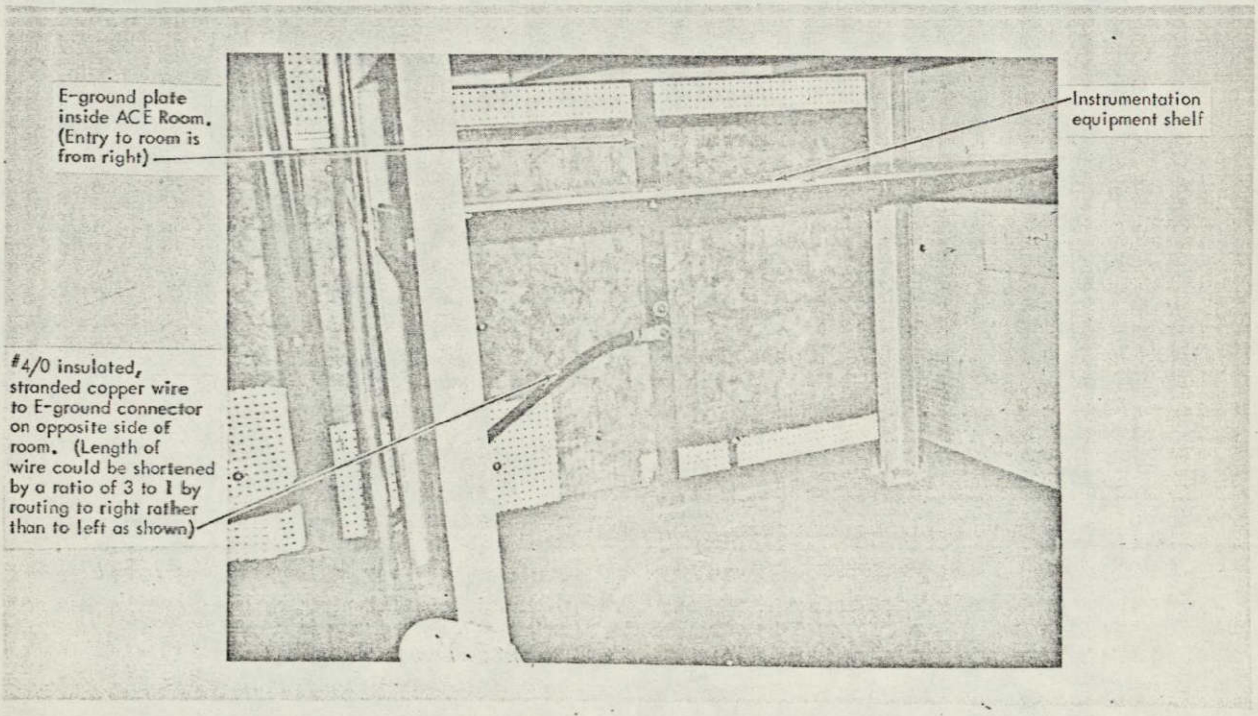

Figure 3-14 LUT-1 - ACE Room E Ground. Cable shown runs 14 feet to a point 5 feet away.

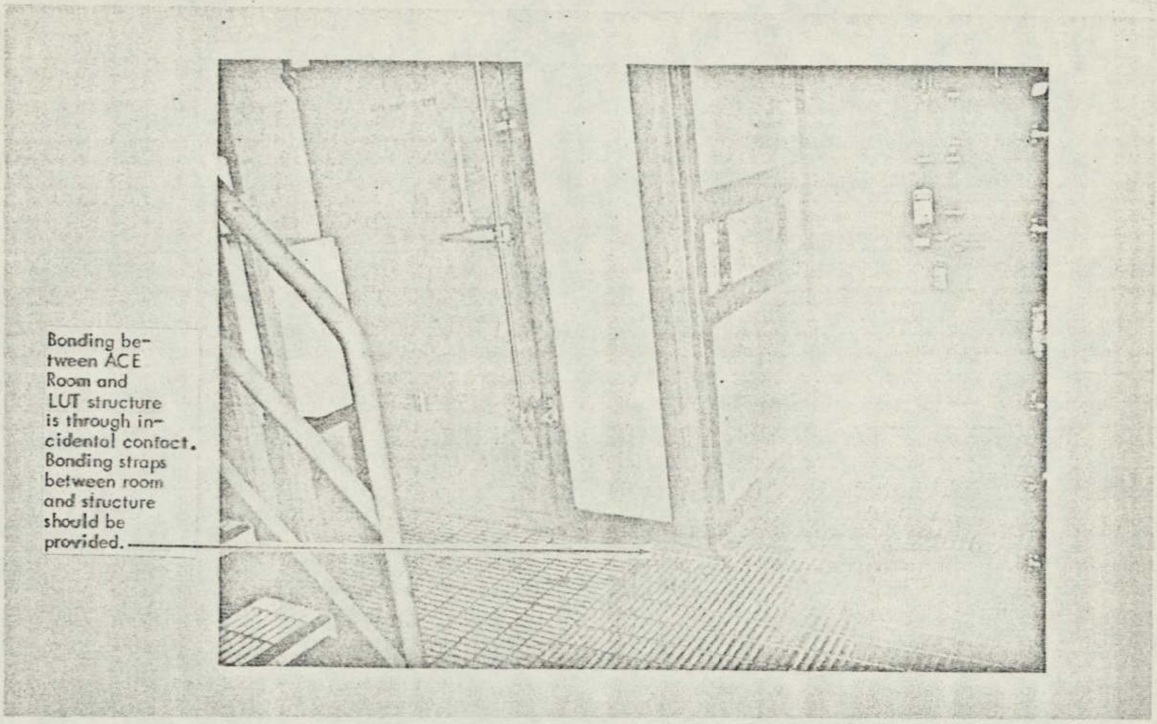

Figure 3-15 LUT-2, ACE Room, 280-Foot Level. Note lack of bonding to structure. Impedance as high as 70 ohms has been measured.

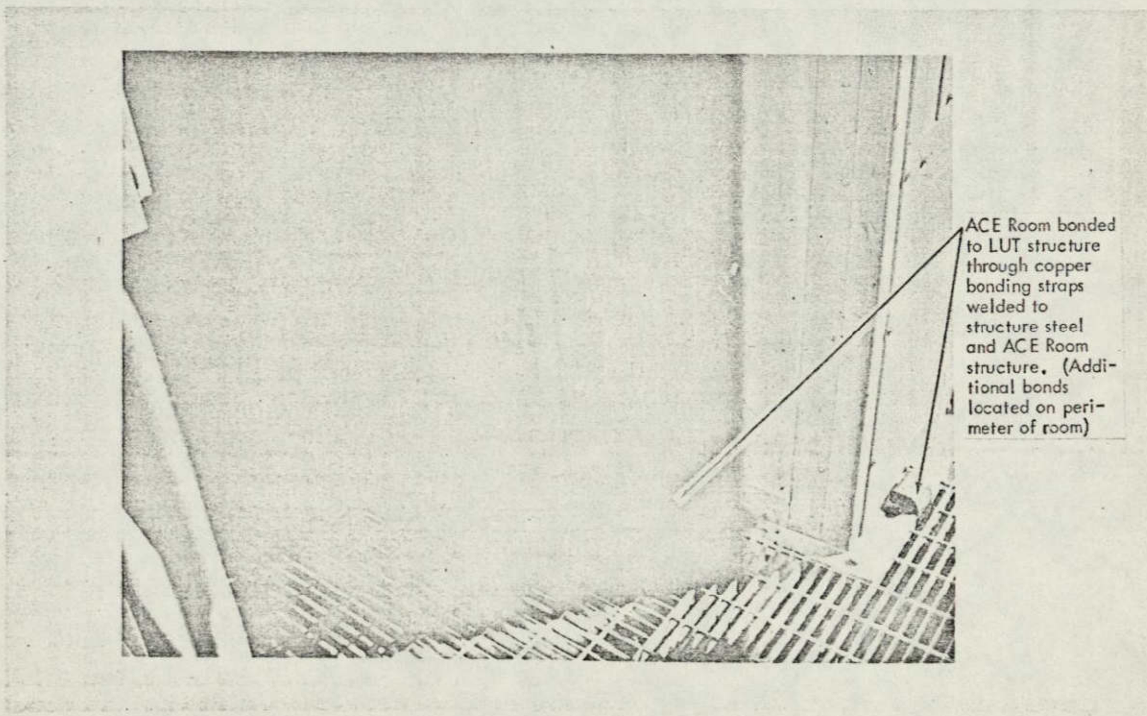

Figure 3-16 LC-39, LUT 3, ACE Room. Note bonding of room to structure.

- In LUT 3, a temporary cable entrance hole had been cut in the bulkhead. This hole provides an EMI compromise, can cause cable damage since no mechanical protection was provided, and will not permit the room to be pressurized before launch.

- Unit C14-205 is in series between the ground lead from TD9074 and five other units in the ACE Room.

- All disconnect terminals for the LUT EGP ground cables were not treated with a protective coating. Figures 3-17 and 3-18 illustrate this condition.

- The I-Ground feeder to the ACE functions primarily as a 28-volt dc return. There is no quiet ground for ground reference.

3.2.3 Launch Complex 34 (LC-34)

3.2.3.1 General. Launch Complex 34 is located on the Cape Kennedy AFS and is arranged for the assembly, checkout, servicing, and launch of Saturn I vehicles. It will more than likely be used for the SKYLAB Program (formally Apollo Applications Program). The complex includes a blockhouse, AGCS Building (underground), ECS Building, umbilical tower, launch pedestal, Mobile Service Structure, and service facilities for LOX, LH_2, RP-1, and high pressure gas. The Mobile Service Structure is mounted on rails so it can be moved from the vicinity of the launch pedestal to a point several hundred feet away prior to launch.

3.2.3.2 LC-34 Grounding System. The grounding system for this complex includes a number of subsystems. In the blockhouse, the majority of the equipment is grounded to the ac ground. This ground originates from the neutral of the power distribution system and is connected to building steel and an external ground grid. Portions of the ACE system are implemented with a static and signal ground - both one-inch copper pipes wrapped with green and black tape, respectively. All of these grounds terminate in a common plate (single-point ground bus) beneath TD140A1. Also connected to this plate are two 500-MCM cables which follow the cable terminal to the AGCS Building in the launch area. These terminate in the common I-Ground point in the AGCS and in Rack 1301A6 in the computer room. The AGCS includes an extensive I-Ground system as well as the ac ground. This area was sealed and no inspection could be made. The pad area is grounded primarily by a peripheral grid of rods interconnected with buried #4/0 AWG bare cable. Connected to this grid are extensions to the LH_2, LOX, RP-1, and HP gas areas. All cable runs and fuel lines are protected against lightning by a static line run above the cable tray or pipe tunnel. The umbilical tower is provided with E- and I-Ground systems. E-plates are provided for the swing arms at the 100-foot, 120-foot, 170-foot, and 210-foot levels. E- and I-plates are provided for the ACE room at the 200-foot and 210-foot levels.

The Mobile Service Structure includes E- and I-Ground distribution systems. The common ground points for these two systems are steel blocks which bear on the rails (Figure 3-19) on which the structure rolls; one is provided for each side of the tower. Unless special precautions are observed in mating the shoe to the rail, a high resistance bond will result. The E- and I-Grounds are routed to the using

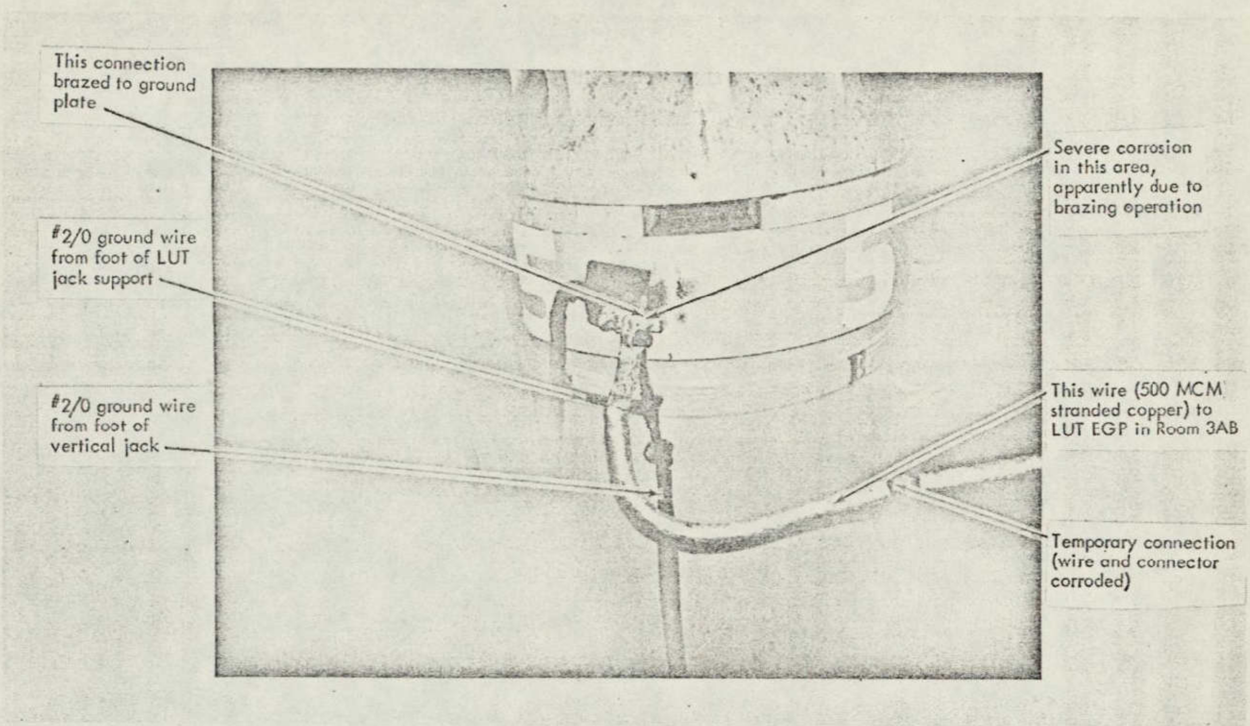

Figure 3-17 LUT-1, Leg 5, Bay 2, VAB - Earth Ground Connection for LUT. Note excessive corrosion at connecting point. Connection is less than 3-months old.

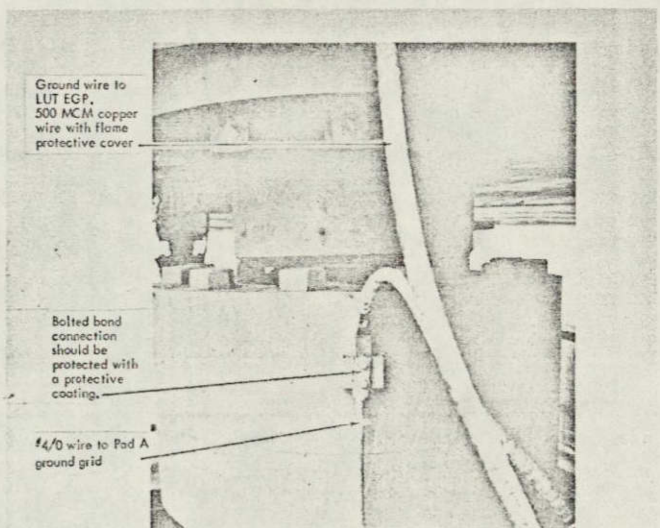

Figure 3-18 LC-39, Pad A-Ground Connection for LUT. Note lack of protection on lower half of connection.

levels using #2/0 welding cable. These cables are in the open risers with power and instrumentation cables. The lower platforms (2, 3, and 4) are provided with ground attachment points which are connected through 4/0 welding cable to building steel of the fixed portion of the MSS. Platform 5 at the 172-foot level has an E-plate only, while Platforms 6, 7, and 8 at the 194-foot, 203-foot, and 213-foot levels are equipped with both E- and I-plates.

3.2.3.3 LC-34 Grounding Anomalies. The following anomalies were found in the grounding system of LC-34:

- The condition of the grounding system in general is rather degraded from lack of maintenance (Figure 3-20). Temporary connections and branches have been made to the original system with no apparent consideration of compromises and loops created.

- E- and I-Ground cables have been run together with power cables, with no consideration for noise isolation.

- The gauges of many cables are inconsistent with the length of the run. For example, the I-Ground riser in the Launcher/Umbilical Tower is #2/0 AWG cable. For the length of run involved, this cable should be 500 MCM.

- The grounding shoes bearing on the rails are shared for the E-, I-, and lightning grounds. Measurement of the contact resistance of one of the shoes gave a resistance of 144 milliohms. MIL-B-5087B (ASG) indicates a minimum bonding resistance of hundredths of milliohms for currents of the magnitude experienced in a lightning strike.

- Many common-mode loops appear to exist within the various subsystems of the complex. For example, common-mode loops exist where portions of the ACE system interconnect with portions of other systems associated with the ac or I-Ground.

3.2.4 Launch Complex 37 (LC-37)

Launch Complex 37 (LC-37) is adjacent to LC-34 and is arranged for the assembly, checkout, and launch of Saturn I vehicles. It is very similar to LC-34 except that two umbilical towers are provided and the MSS is arranged differently. The MSS shuttles between the two umbilical towers on rails.

At the time of the evaluation, there were no plans for the future use of this facility and, accordingly, in the interest of conservation of available time, only a cursory examination was made. The comments made with regard to LC-34 generally apply to LC-37.

3.2.5 Manned Spacecraft Operations Building

3.2.5.1 General. The Manned Spacecraft Operations Building (MSO), located in the KSC Industrial Area, is the focal point for the majority of the work in assembling,

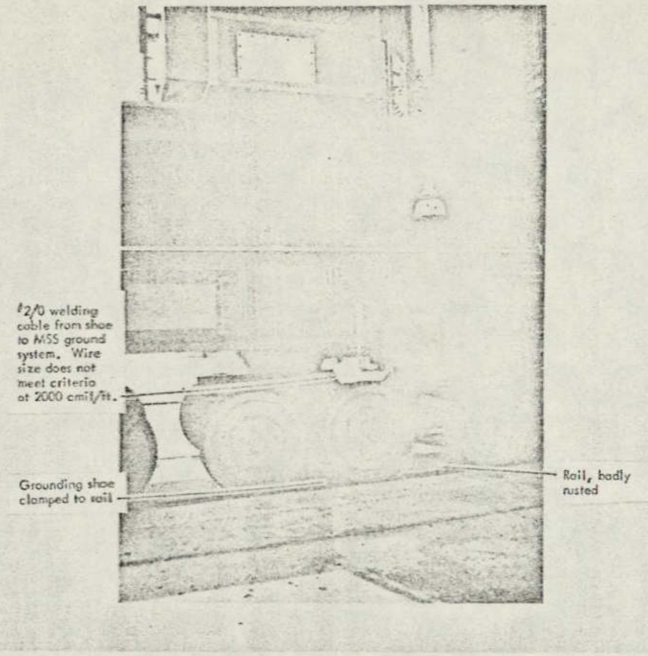

Figure 3-19 LC-34 - Typical Ground Shoe for MSS. Notice corrosion on track and connecting cables. Shoe-to-track resistance was measured at 142 milliohms.

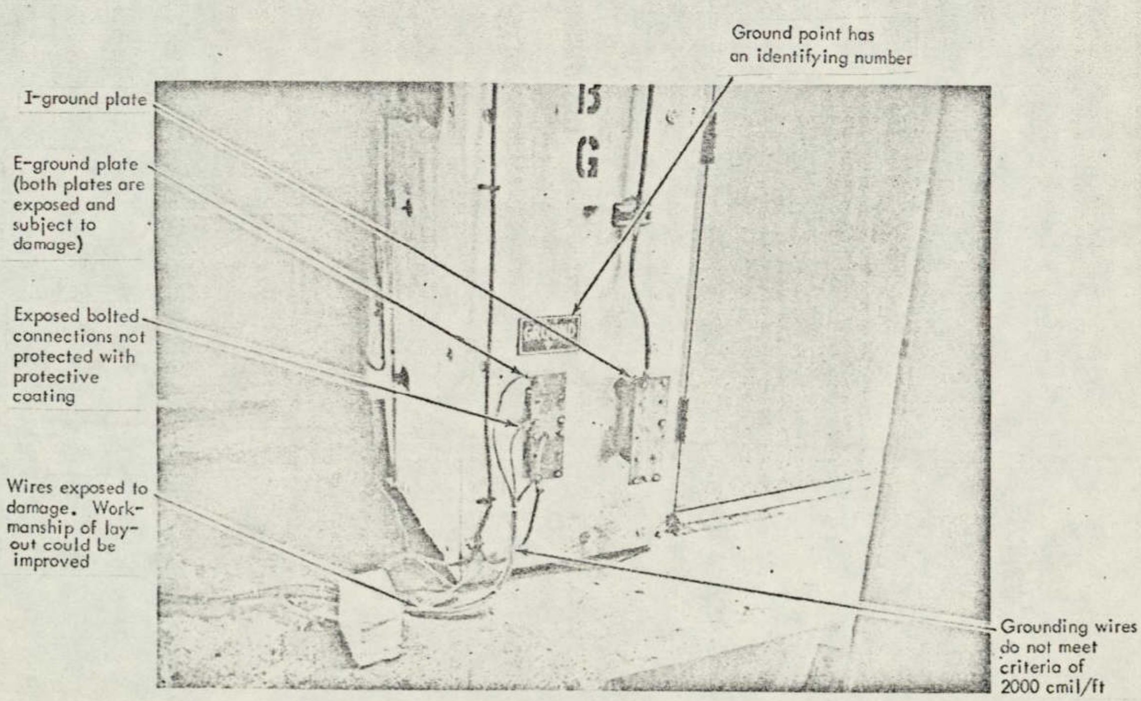

Figure 3-20 LC-34, Umbilical Tower - E-Ground and I-Ground Plates. Note corrosion and random laying of E-ground cables.

checking out, and mission rehearsal for the Apollo Command Module, Service Module, and Lunar Excursion Module. The front part of the building is primarily office space. It is only the rear section of the building which concerns this evaluation. This portion of the building contains a low-bay area which includes office, laboratory, and control room facilities. Adjacent to the low-bay area is a high-bay area which includes two altitude chambers and two spacecraft test stands.

3.2.5.2 MSO Grounding System. The MSO grounding system includes four subsystems: the E-Ground, I-Ground, L-Ground, and A-Ground. The E- and I-Grounds are equipment and instrumentation grounds, respectively, and are distributed within the building using three-inch copper pipe and #2/0 AWG cable. The L-Ground, implemented with an eight-inch aluminum pipe, is designated as an L/M Ground but appears to be used to select between two ground points and two building steel connections. The A-Ground is implemented with a one-inch copper pipe and serves as a ground for the antennas on the roof of the high-bay portion of the building. Although time permitted only a small portion of the building ground system to be inspected, it appears that the implementation of the grounding system in this facility is the best of all KSC areas.

3.2.5.3 MSO Grounding Anomalies. The following anomalies were found in the brief inspection of MSO grounding systems:

- In the CURFCOE Room (3227), a busbar riser is installed to interconnect the I-Ground to the power filter cabinet. This busbar is wrapped with plastic tape and is being intermittently compromised where the sharp edge of a cutout in the raised floor panel has cut through the tape. This edge comes in contact with the busbar whenever one steps on the panel.

- A lightning arrestor installed between the A-Ground and building steel on the roof of the high-bay area is of an inferior type and should be replaced with a better grade similar to that installed in Room 1E3 of the VAB.

- An anemometer installed on the roof is above the cone of protection of any air terminal. It appears that an air terminal may have been installed on this mast at one time but is broken off.

- A stile-type stairway is provided on the high-bay roof to cross a 3 x 6 foot air conditioning duct. The nearest air terminal is a 2-foot aluminum rod located in the center of the duct approximately 5 feet from the stile. This is, therefore, a hazard to personnel. (See Figure 3-21.)

- The air terminals installed on the air conditioning duct are aluminum and are connected to building steel by #0 AWG aluminum wire. This wire is connected at both ends by galvanized messenger clamps. In addition, the wire is bent with a one-inch radius where it passes over the edge of the duct. KSC-STD-E-0013, Paragraph 3.5.1.8, stipulates a minimum bending radius of eight inches.

- Several of the messenger clamps on the building steel studs are loose to the point where they may be pulled off by hand.

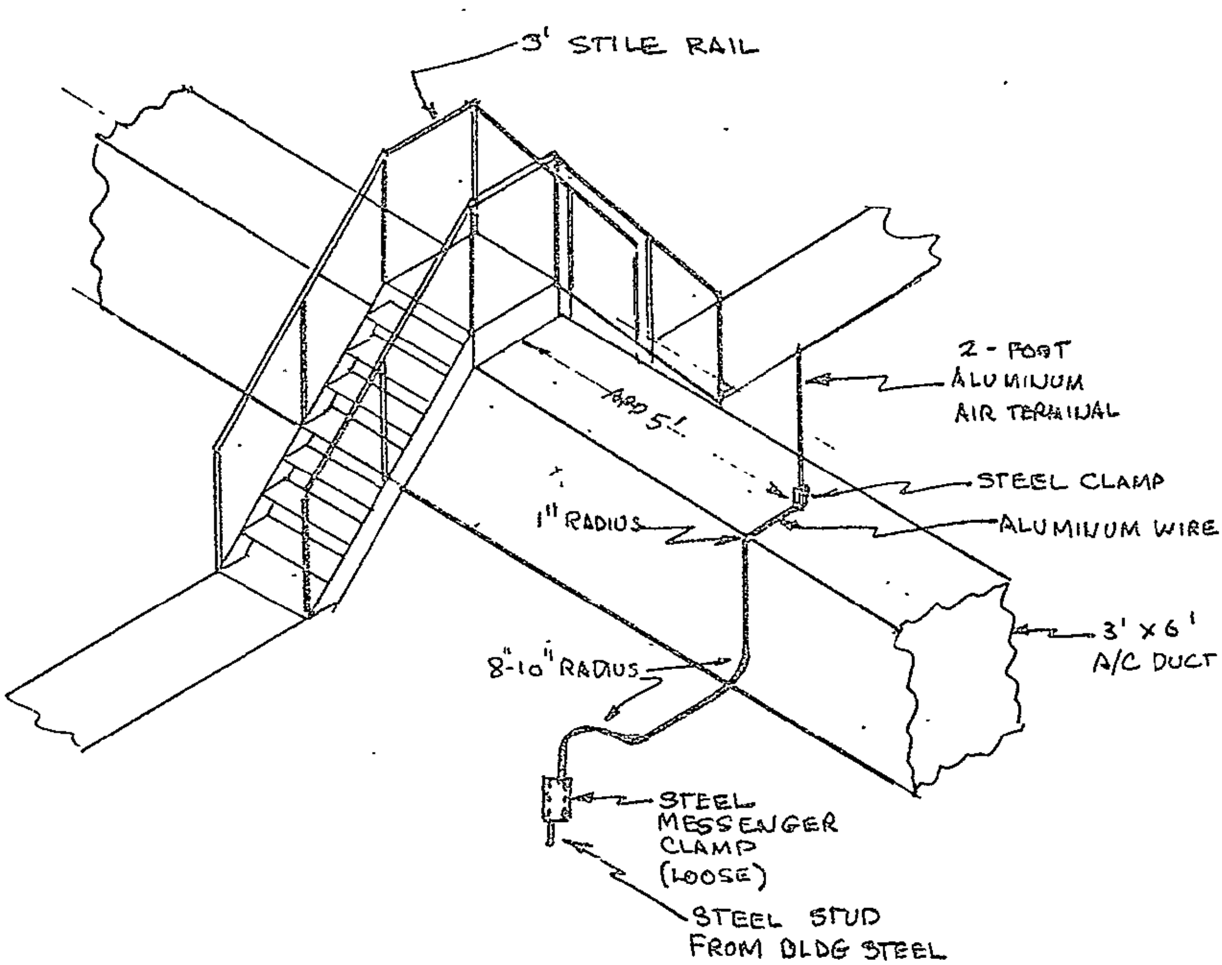

Figure 3-21 MSO Building - Lightning Hazard

3.3 GROUND RESISTANCE AND RESISTIVITY MEASUREMENTS

3.3.1 Introduction

Ground resistance and ground resistivity measurements were made at several locations in Launch Complexes 39, 37, and 34. In general, the resistance of the ground points measured was less than 1.0 ohm and complies with criteria given in KSC-STD-E-0012, December 1969. The earth resistivity, with one exception, was found to be that expected for low lying coastal land. The one exception was the layer of sand and shell in the general vicinity of the VAB. Details of the measurements are given in the following paragraphs.

Ground resistance and resistivity measurements were made using the method described in Paragraph 3.5.3.4.2.2 of Volume I of this report. An Associated Research Model 293 Vibroground test set was used for making the measurements. The three-stake method illustrated in Figure 3-22 was used for ground resistance measurements and the four-stake method shown in Figure 3-23 was used for resistivity measurements.

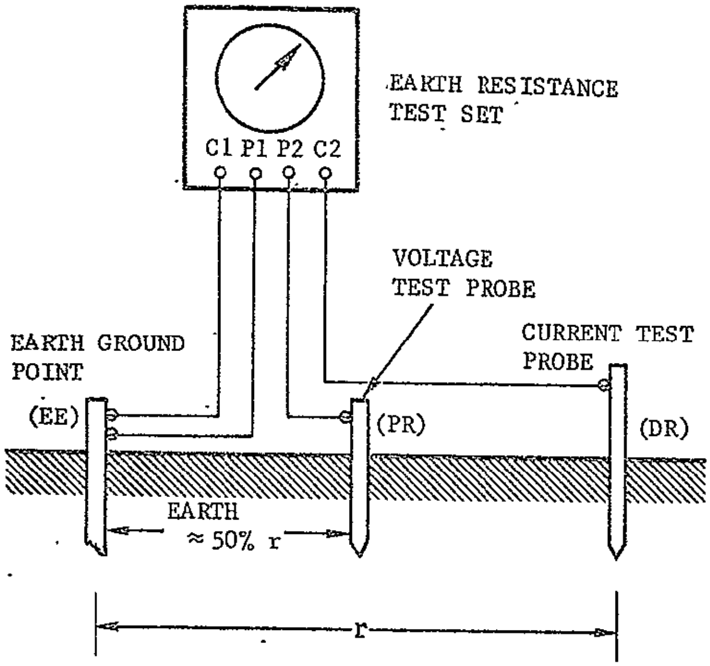

Figure 3-22 Earth Resistance Measurement, Three-Stake Method

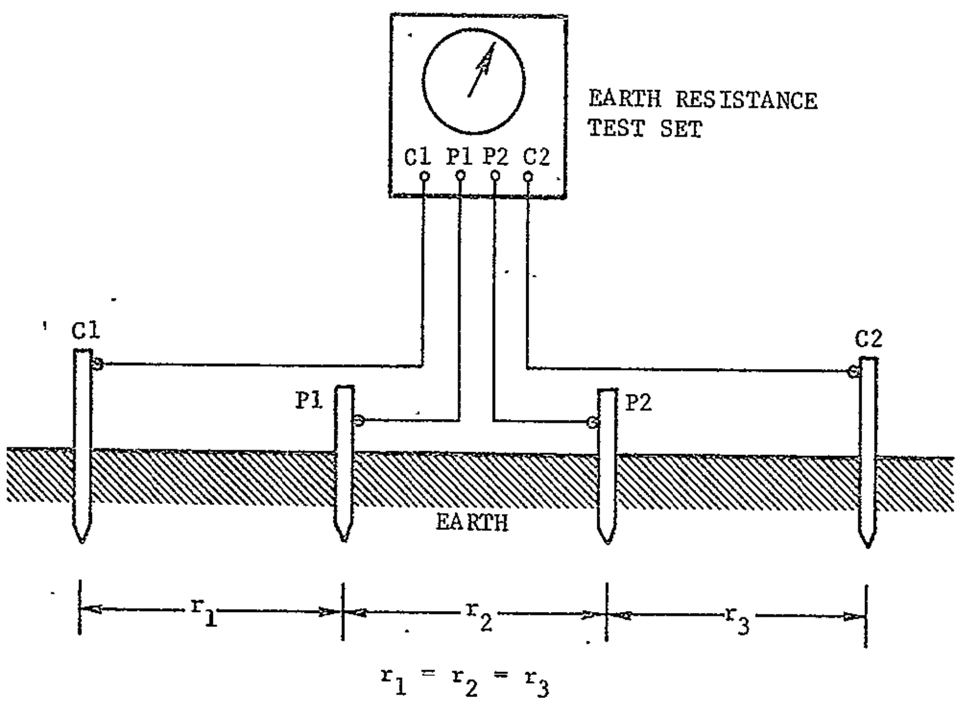

Figure 3-23 Earth Resistivity Measurement, Four-Stake Method

3.3.2 Vehicle Assembly Building

3.3.2.1 Ground Resistance

a. Instrumentation Ground, Tower A. The ground resistance for Tower A ground grid measured less than 100 milliohms. To assure that the measurement was only for the grid, the grid extension to the tower ground riser was disconnected at the point where the grid conduit entered the VAB. Measurements were made using the three-point method and the test stakes were oriented in both the east-west line and north-south line.

b. Building E-Ground. The ground resistance for the E-Ground measured less than 100 milliohms. The test point was at the jack supporting sides 2 and 3 of the Launch Umbilical Tower in Bay 1. Orientation of the test stakes was the same as for the I-Ground resistance measurement.

3.3.2.2 Ground Resistivity. Resistivity measurements were made at several locations near the VAB. The results of the measurements are tabulated in Table 3-1.

TABLE 3-1

GROUND RESISTIVITY - VAB.

No.	Location	Test Stake Alignment	Test Stake Spacing (ft)	Resistivity (ohm-cm)
1	North side of temporary parking lot located east of VAB near turn basin.	East-West	4	85,000
			8	58,220
		North-South	16	18,340
			16	18,340
2	1000 feet east of VAB and 100 feet north of crawler-way.	North-South	10	149,000
			20	49,600
		East-West	30	22,900
			30	22,900
3	100 feet west of VAB and 20 feet north of crawler-way.	East-West	10	24,900
			20	9,260
		North-South	10	12,060
			20	3,180

The resistivities listed in row No. 2 of the table are considered to be typical of the resistivities to be encountered for undisturbed soil in the general area of the VAB. Measurement No. 1 was taken in the area which may have been disturbed by construction or earth-fill operations, and measurement No. 3 was taken in an area in which there are buried metallic objects such as conduits, wire, etc., which would cause unrealistically low resistivity readings.

Judging from the resistivity value listed for measurement No. 2, or No. 1 for that matter, it would appear that a value of ground resistance as low as that measured for I-Ground grid A would not be attained with the grid configuration used, i.e., three 40-foot ground rods spaced about the corners of a 50-foot equilateral triangle.

An indication of the ground resistance that could be expected for a ground point in uniform earth of 229 ohm-meters (22,900 ohm-cm) resistivity can be calculated using (1) as a guide.

$$R = \frac{P}{2L}\left(\log_e \frac{4L}{a} - 1\right) \tag{1}$$

where

R = ground resistance

P = ground resistivity in ohm-meters

L = length of rod in meters

a = radius of rod in meters

Using a resistivity of 229 ohm-meters, rod length of 13 meters, and a radius of 0.0095 meter

$$R = \frac{229}{6.28 \times 13}\left(\mathrm{Log}_e \frac{52}{0.0095} - 1\right)$$

$$R = 2.8 \times 5.60 = 15.7 \text{ ohms}$$

Allowing for the effects of mutual resistance between three 40-foot rods spaced at intervals of 50 feet around the circumference of a circle of 29-foot radius as in the grid, the total resistance of the ground grid is 0.45 x 15.7, or 7.06 ohms. The earth ground resistance of the interconnecting wires between the rods is approximately 44 ohms and would not significantly reduce the total resistance of the ground grid. Therefore, the lowest resistance that could be expected for the measured resistivity would be approximately 7.0 ohms rather than the very low resistance measured.

The measured ground resistance may be approximated by assuming that the vertical structure of the earth in the general vicinity of the measurement is not uniform but consists of two layers, a surface strata of high resistivity and a subterranean strata which has a lower resistivity. Test borings at the VAB have shown that the earth in that vicinity does in fact consist of a surface strata of sand and shell to a depth of 60 feet and a second strata to a depth of 120 feet, which consists of clayey sand and silt (see Figure 3-24). Assuming that the lower strata exists in a climate of 40 percent sea water, the resistivity would ordinarily be 300 to 1000 ohm-cm (3 to 10 ohm-meters) and the apparent resistivity would vary between the limits of P_1 (surface resistivity) and P_2 (subterranean resistivity), depending upon the depth to which the ground rod extended.

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(1) Earth Conduction Effects in Transmission Systems, Erling D. Sunde, D. Van Nostrand, 1949.

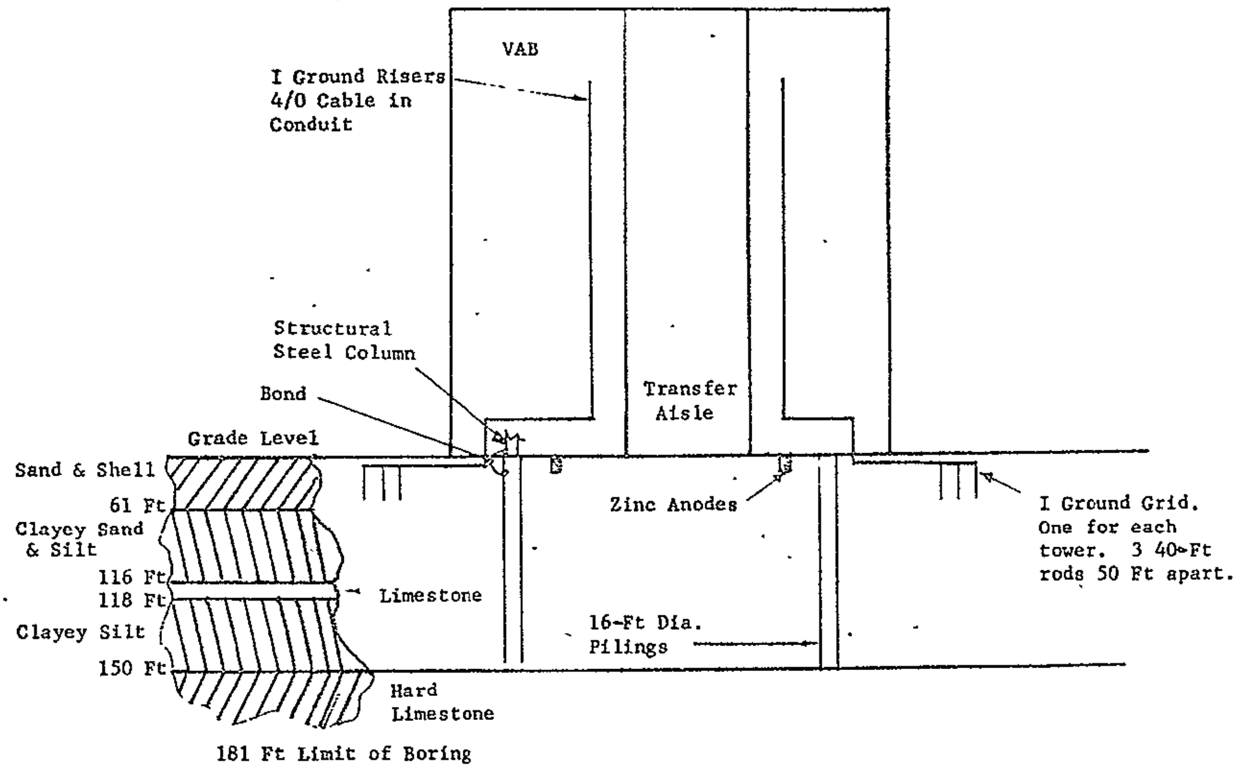


Figure 3-24 Typical VAB Ground

Using the approach given in Pages 47 to 51 of (1) and a condition of

P_1 = 229 ohm-meters

P_2 = 10 ohm-meters

r = 40 feet (depth of ground rod)

d = 60 feet (depth of surface strata)

The value for a ground grid of the configuration used for I-Ground would calculate to approximately 300 milliohms with ground rods of 40 foot length. This value would be further reduced by the fact that conducting materials are buried in the soil in the immediate vicinity of the grid. From the above, it would appear that the low measured ground resistance is theoretically attainable even though the worst case condition for the resistivity of the lower strata is assumed for the purpose of theoretical approach.

3.3.3 Crawlerway

Two measurements of ground resistivity were made in the crawlerway roadbed at a location approximately 1000 feet east of the VAB and in the same area as VAB resistivity measurement No. 2. The results of the measurements are tabulated in Table 3-2.

TABLE 3-2

CRAWLERWAY GROUND RESISTIVITY

Location	Test Stake Alignment	Test Stake Spacing (ft)	Resistivity (ohm-cm)
Parallel to crawlerway in north track	East-West	4 8	34,140 19,900
Median strip between crawler-way tracks.	East-West North-South	16 13	15,630 14,920

The resistivities measured for the median strip appear to be contrary to that which would be expected. The design for the crawlerway specifies that a conductor of #4/0 bare copper wire is buried beneath the length of the crawlerway and attaches to the E-Ground system at the VAB, LC-39 Pads A and B. This wire is designed to provide lightning protection through the crawler drag chain when the crawler is on the roadbed. If the wire were present, the resistivity measured with the stakes in the east-west direction (the direction of the axis of the wire) in the median strip should be of a lower value than that in the north-south direction, whereas the measured values are within 5%. The values measured are considerably lower than for the area 100 feet north of the crawlerway; this may be due to lower resistivity, compacted fill, or conducting material buried in the area which is not necessarily oriented along the crawlerway and may not be sufficient for the intended purpose of a lightning protection conductor.

From the above, it would appear that this area is a subject for further investigation.

3.3.4 Launch Pad LC-39B

3.3.4.1 Ground Resistance. The ground resistance for Launch Pad B measured less than 100 milliohms. Two readings were taken, one with the test stakes oriented on an east-west line and the second at 35 degrees south of the original line. Measurements were made at the entrance of the cable tunnel. A large lead-covered cable is buried adjacent to the 270 degree route, and there is very likely other conducting material buried within the launch complex that would tend to lower the measured resistance. In any event, a low ground resistance is to be expected in this area because of the low ground resistivity as explained in Paragraph 3.3.4.2.

3.3.4.2 Ground Resistivity. Several measurements of ground resistivity made in the area of LC-39B were found to be very low. This Launch Pad is located near the beach of Merritt Island and the resistivities obtained are to be expected. The results of the measurements are tabulated in Table 3-3.

TABLE 3-3

LC-39B GROUND RESISTIVITY

Location	Test Stake Alignment	Test Stake Spacing (ft)	Resistivity (ohm-cm)
At cable tunnel entrance to pad	East-West	4	1,379
		8	1,532
		16	1,042
	North-South	16	1,042
East side of LC-39 parking lot	East-West	10	1,149
		20	100-300*
	North-South	20	100-300*

*This resistivity measurement was at the lower limits of accuracy of the test instrument.

3.3.5 Launch Complex 34

3.3.5.1 Ground Resistance

a. Mobile Service Structure (MSS). The earth ground connection for the Mobile Service Structure is through a metal contact shoe that clamps against the rail of the MSS transport system; the rail system in turn is connected to a ground grid. See Figure 3-25 for a simplified line drawing of the ground mechanism. Figure 3-19 also illustrates the rail clamp ground connection. At the time of measurement, the contact resistance between the rail and the shoe was 144 milliohms, which exceeds the criteria of 0.5 milliohm listed in STD-E-0012. The total resistance from the MSS to earth was 815 milliohms, including the contact resistance.

To avoid the high resistance of the shoe-to-rail bond, the MSS should be provided with a plug-in type connector that will assure a low bonding contact and also the capabilities of convenient connect/disconnect. Figure 3-26 is a simplified illustration of an approach that could be used. As it is now, the shoe-to-rail bonding resistance would very likely exhibit undesirable characteristics in the event of a high amplitude current discharge such as would occur in the event of a lightning strike. As an illustration, if a lightning strike of 100 microseconds duration and an average current of 10,000 amperes were to strike the MSS tower and flow to ground through the shoe-to-rail bond, the voltage developed across the bond would be 1440 volts, which is hazardous to personnel.

$$V = 0.144 \text{ ohm} \times 10{,}000 \text{ amp} = 1440 \text{ volts}$$

The heating effect would be:

$$H = 0.239 \times 0.144 \text{ ohm} \times 100 \text{ microseconds} = 3442 \text{ calories}$$

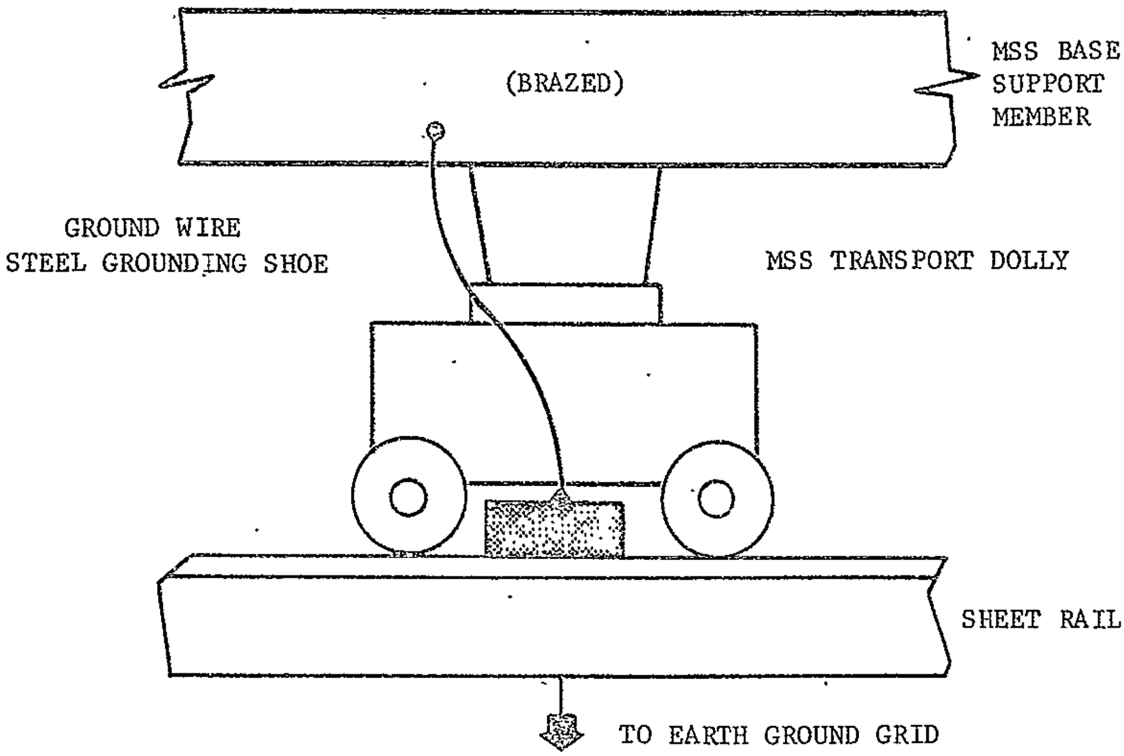


Figure 3-25 MSS Ground Connection (Typical)

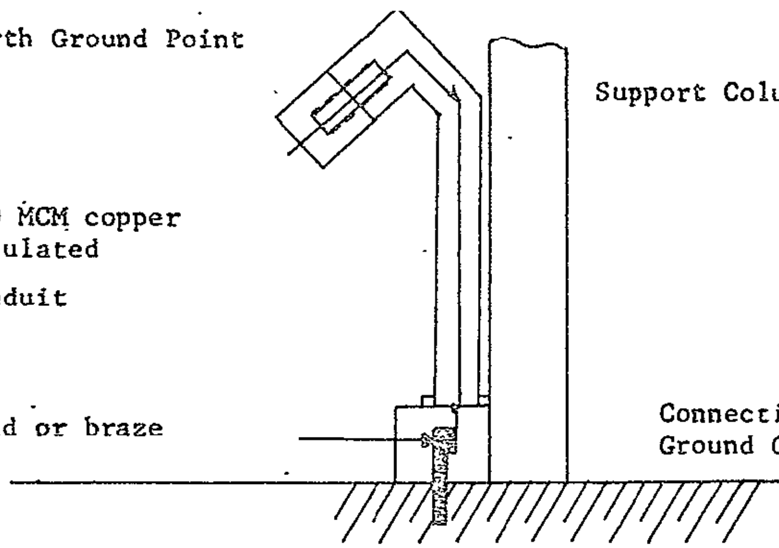
This amount of heat generated in the electrical contact area of the bond would quite likely cause considerable physical damage, especially if moisture were entrapped within the bonding area.

b. Umbilical Tower. The ground resistance for the tower ground point measured 715 milliohms, which is within the criteria of 1.0 ohm.

3.4 NOISE MAPPING

3.4.1 Introduction

One of the most significant measures of the effectiveness of a grounding system is the amplitude of the noise voltages that appear on the grounding bus at a point remote from the ground connection. This section reports the results of noise measurements in both the frequency and time domains on various portions of the grounding system for the VAB, LCC, LC-39, Pad A, and the MSOB.



Note: 1. Moisture proof. Contact resistance should not exceed 0.5 milliohm.

Figure 3-26 Recommended Earth Ground Point Connection for LC-34 MSS (Typical)

3.4.2 Measurement Methods

Noise measurements were made using a Tektronix 547 oscilloscope and associated plug-in units, Type L for time domain in the band of 3 Hz to 24 MHz, and Types 1L-5, 1L-10, and 1L-20 for frequency domain measurements in the band of 10 Hz to 4.2 GHz.

Figure 3-27 is an illustration of the manner in which the oscilloscope was set up for test measurements. The "green wire" of the power cord was not connected normally so that the scope chassis ground would be connected to the reference ground point through the RG-59 coaxial cable center conducter. With the test cables and ground lead connected as shown, both leads are electrostatically shielded.

Photographs were taken of the oscilloscope displays and are reproduced in this report to illustrate the nature of the voltages at various locations in Launch Complex 39. In all photographs, time or frequency increases from left to right.

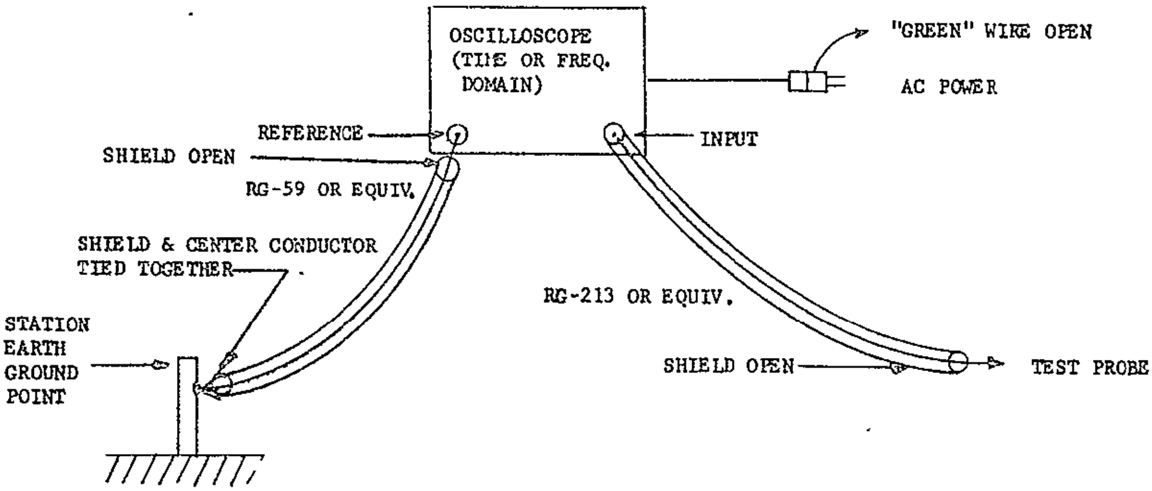


Figure 3-27 Test Equipment Configuration for Time and Frequency Domain Measurements

3.4.3 Vehicle Assembly Building (VAB) Tests

3.4.3.1 General. Time and frequency domain measurements were made at selected points in the VAB for both E-(Building) and I-(instrumentation) grounds. In general, the voltages measured were relatively low; the maximum observed during the test period was 1 millivolt (mV) for certain transient signals.

3.4.3.2 Building Steel (E) Measurement. With the test probe attached to a steel building support member and the reference probe attached to the I-Ground wire riser at the first floor of the corresponding tower (A or E), the noise spectra observed were as shown in Figures 3-28, 3-29 and 3-30. The maximum noise voltage is 62 microvolts (μV) at 730 kHz, Figure 3-29.

The spectra shown in Figures 3-29 and 3-30 were taken with the probe attached to the same location in Room 26E5. The first figure is representative of the noise spectrum to be expected during a normal workday; the second is representative of the spectrum on a Saturday. It is interesting to note that the spectrum characteristics for the two measurements are similar, but the maximum voltage drops from 62 to 15 μV or a drop of 12.6 dB. Figure 3-31 is a photograph taken with the test probe lying open on the 25th floor to illustrate the low ambient noise voltages in the test cable.

In the spectrum of 1 MHz to 36 MHz, there were no noise voltages higher than 20 μV.

Probe on building steel in Room 25A3, referenced on I-Ground in Room 1A3.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Horizontal
0.02 mV/cm Vertical
(Disregard pulse at start of trace)

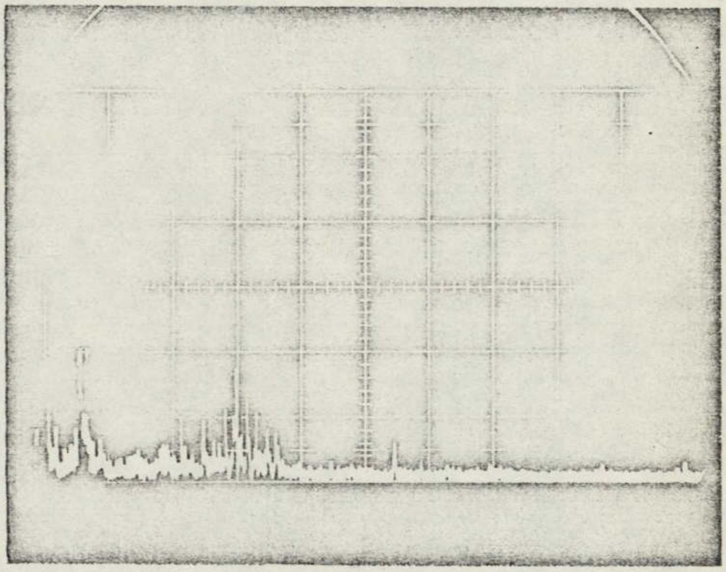


Figure 3-28 Noise Voltage in Frequency Domain, VAB Steel, Tower A

Probe in building steel in Room 20E5, referenced on I-Ground in Room 1E3.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Horizontal
0.02 mV/cm Vertical
(Disregard pulse at start of trace)

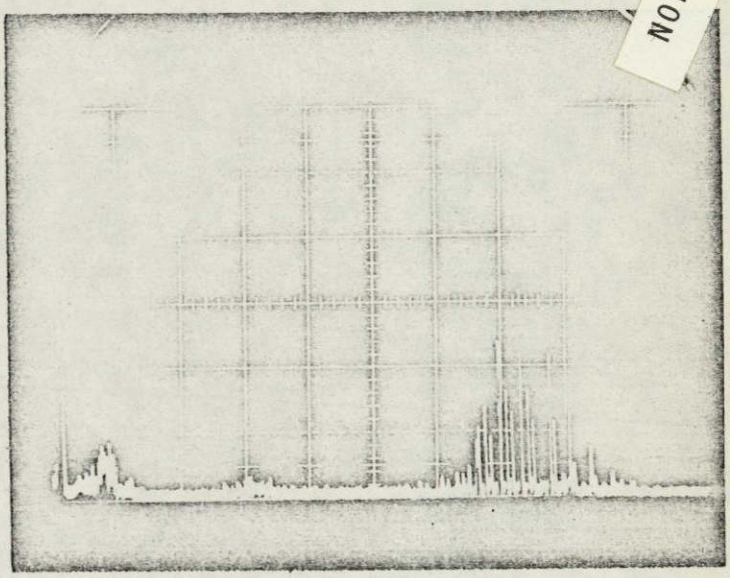


Figure 3-29 Noise Voltage in Frequency Domain, VAB Steel, Tower E

Probe on building steel in Room 26E5, referenced on I-Ground in Room 1E3.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Horizontal
0.01 mV/cm Vertical
(Disregard pulse at start of trace)

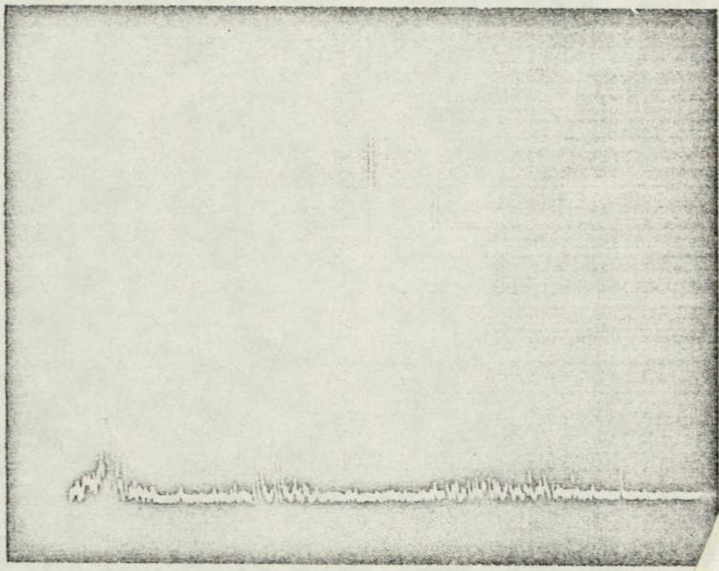


Figure 3-30 Noise Voltage in Frequency Domain VAB Steel, Tower E

Probe open at 25th floor halfway, Tower A, referenced on I-Ground in Room 1A3.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Horizontal
0.02 mV/cm Vertical

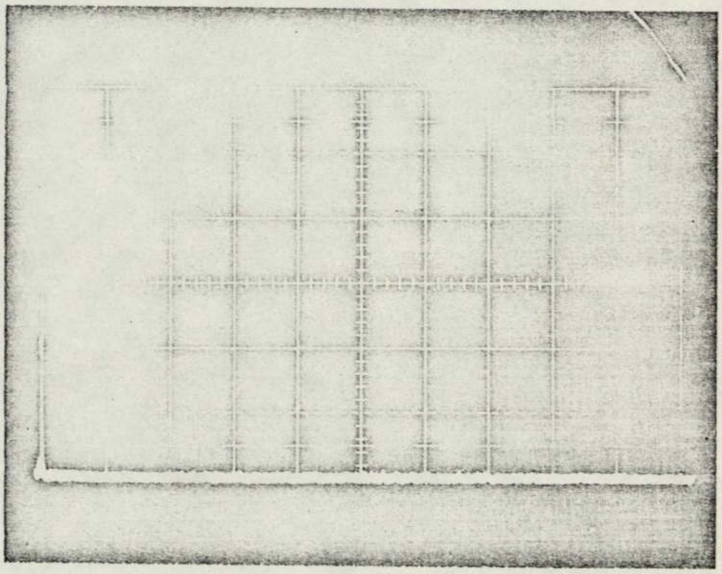


Figure 3-31 Noise Voltage in Frequency Domain, VAB Steel, Tower A

3.4.3.3 Instrumentation (I) Ground Measurements

3.4.3.3.1 General. Measurements in both the frequency and time domains were made on the I-Ground system at selected points in Towers A and E. In general, the measurements show that the noise voltages are confined to the spectrum of 10 Hz to 1 MHz; voltages at frequencies higher than 1 MHz did not exceed 20 μV. Time domain noise voltages were low amplitude 60-cycle waveform with high frequency components present; maximum amplitude was 40 mV peak-to-peak.

3.4.3.3.2 Tower A.

- Ground Riser Entry to VAB. An indication of the noise voltages that can be present on the riser lead between the entry point into the VAB and the vertical portion of the riser is shown in Figures 3-32 and 3-33. Figure 3-34 is a block diagram of the equipment test set-up.

  The noise spectrum shown in Figure 3-32 shows that the maximum noise voltages did not exceed 25 μV in the spectrum of 10 Hz to 1 MHz. In the spectrum above 1 MHz, the noise voltages were less than 5 μV. The 360-cycle, 15 mV waveform shown in Figure 3-33 is typical of the output waveform of the polyphase rectifiers used in the VAB cathodic protection system. This measurement indicates that the A-Ground grid is negative with respect to building steel, which is to be expected because the cathodic protection system uses zinc as a cathode. Measurements of building steel to earth potential during the ground resistivity measurements also indicated that a negative dc potential existed. Appendix A, Paragraph 31.5 of Volume I of this report, explains the significance of the cathode protection voltage appearing on the A-Ground riser.

- Tower A Noise Mapping. Figure 3-35 shows the frequency spectrum between 10 Hz and 1 MHz measured between the first floor and the third floor, where the riser lead ended. The spectrum is reasonably quiet, not exceeding 500 μv.

  The spectrum shows a 480-microvolt constant amplitude signal at 550 kHz, a frequency that appeared at several other locations. A spectrum measurement indicated that there were no modulation sidebands, which eliminates the probability of this being an AM broadcast station. The source of this signal was not discovered during the investigation. The noise spectrum between 100 kHz and 450 kHz remained fairly constant in amplitude and frequency, indicating that the noise is probably generated by constant duty electrical service devices.

  To obtain a measure of the noise spectrum for the riser at the higher floors, the probe was moved to the 25th floor and connected to the riser in Room 25A3. The 10-Hz to 1-MHz spectrum observed at that point is shown in Figure 3-36. The level of noise was rather low, on the order of 60 to 70 μV maximum, with the exception of random high level noise spikes, in the frequency region of 50 kHz to 340 kHz. The amplitude and distribution of the frequencies in this part of the spectrum

Probe on riser entry into VAB, referenced on riser in Room 1A3.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Dispersion
50 ms/cm Horizontal
0.005 mV/cm Vertical
(Disregard pulse at start of trace)

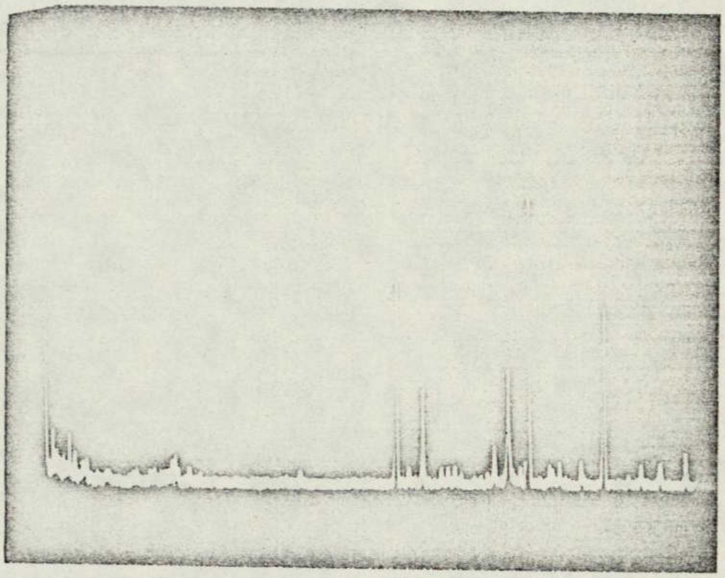


Figure 3-32 Noise Voltage in Frequency Domain, VAB Tower A I Riser

Probe on riser entry into VAB, referenced on riser in Room 1A3.

547 Oscilloscope
1L5 Plug-In, Video Mode
2 ms/cm Horizontal
5 mV/cm Vertical

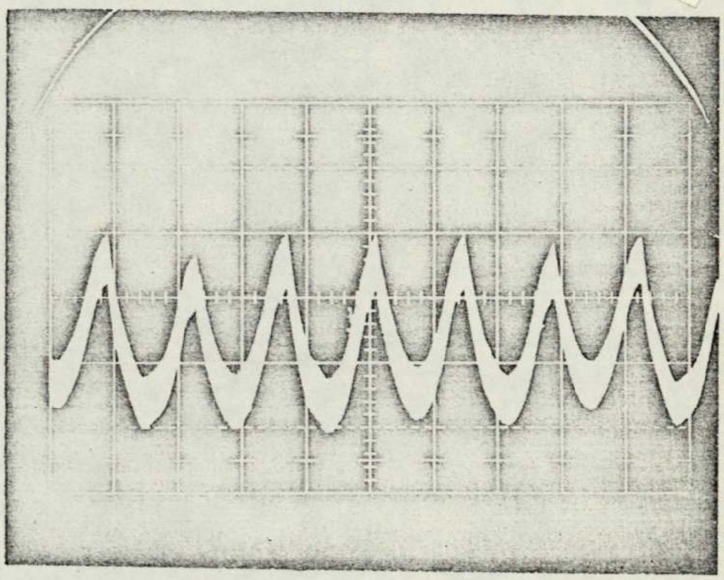


Figure 3-33 Noise Voltages in Time Domain, VAB Tower A I Riser

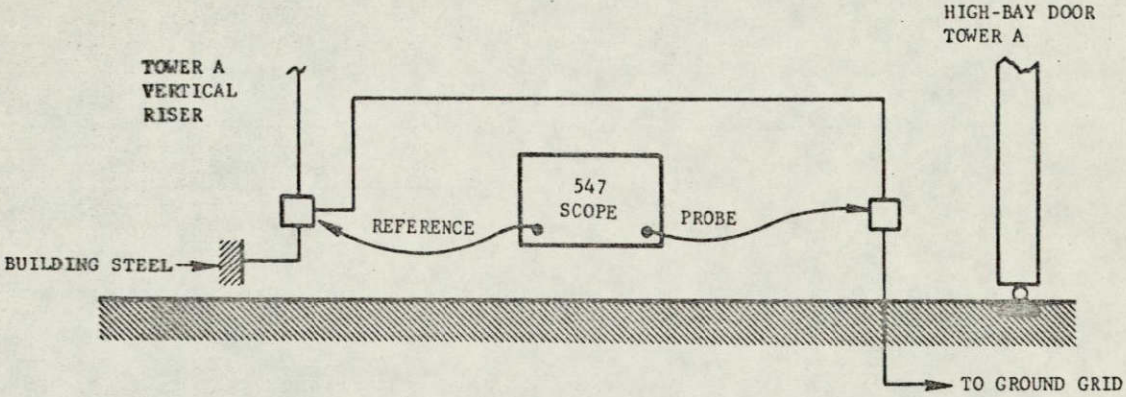


Figure 3-34 Test Equipment Configuration for Measurement at Riser Entry

varied continually; additional data gathered at other locations in KSC indicate that this spectrum of noise may be due in part to the regulating actions of solid state rectifier devices. The random noise spikes were of very short duration and generally exceeded 100 mV in amplitude. Measurement of the characteristics of the pulses was not possible with the noise signal test configuration.

Figure 3-37 is a simplified sketch of the test equipment configuration.

3.4.3.3.3 Tower E, I-Ground. Room 26E7 (IU Test Room) was selected for additional noise mapping measurements in the VAB. The equipment in this room is part of the vehicle checkout equipment and provided an opportunity for measurement at an equipment location that is a part of the vehicle checkout network. For the purpose of this measurement, the test equipment was set up in Room 1E3, the reference test lead connected to the E-Ground riser at that point, and the probe was then extended to Room 26E7. Measurements were made at the I-Ground plate, Rack 11 external ground stud, Rack 12 internal copper ground bus, and at a connection between the equipment racks and building steel (E-Ground).

The grounding system for the equipment racks in this room is tied to I-Ground through a three-inch copper tube that interconnects all racks and then extends to the I-plate. In addition to this, the racks are also connected to building steel through the waveguide support system.

Figures 3-38 through 3-41 show the 10-Hz to 1-MHz spectrum observed during the test measurements. The most interesting point to be observed in these data is that the noise voltages on the I-plate are higher than at the rack ground stud or on the ground bus in Rack 12; the lowest noise voltages were those that appeared on the connecting wire to E-Ground. Based upon these data, it would appear that

Probe on I riser at 3rd floor. Reference on I riser in Room 1A3.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Horizontal
0.10 mv/cm Vertical

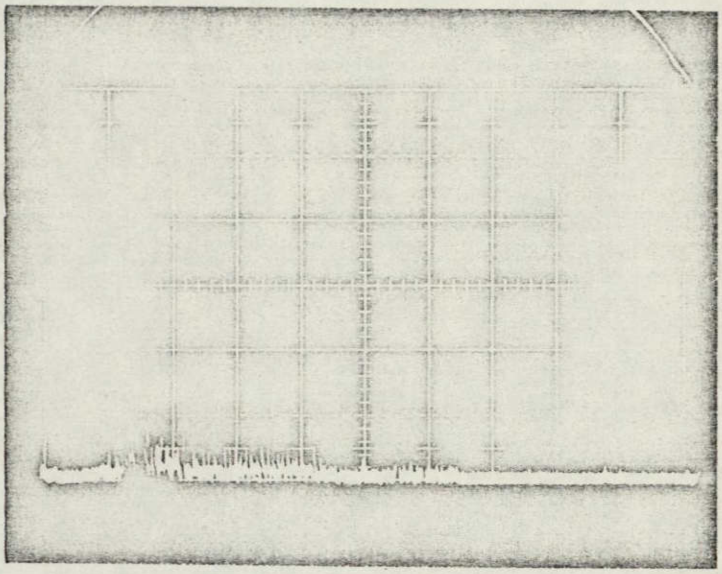


Figure 3-35 Noise Voltage in Frequency Domain, VAB Tower A I Riser

Probe on I riser at 25th floor, referenced on I riser in Room 1A3.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Horizontal
0.02 mV/vm Vertical

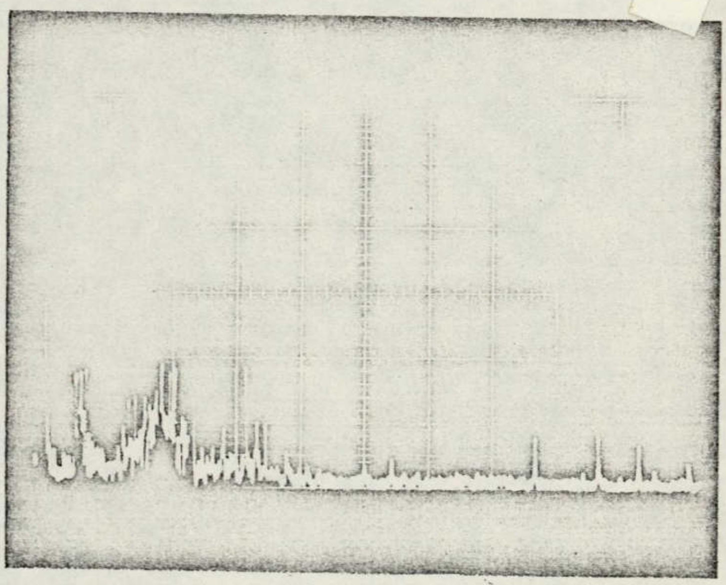


Figure 3-36 Noise Voltage in Frequency Domain, VAB Tower A I Riser

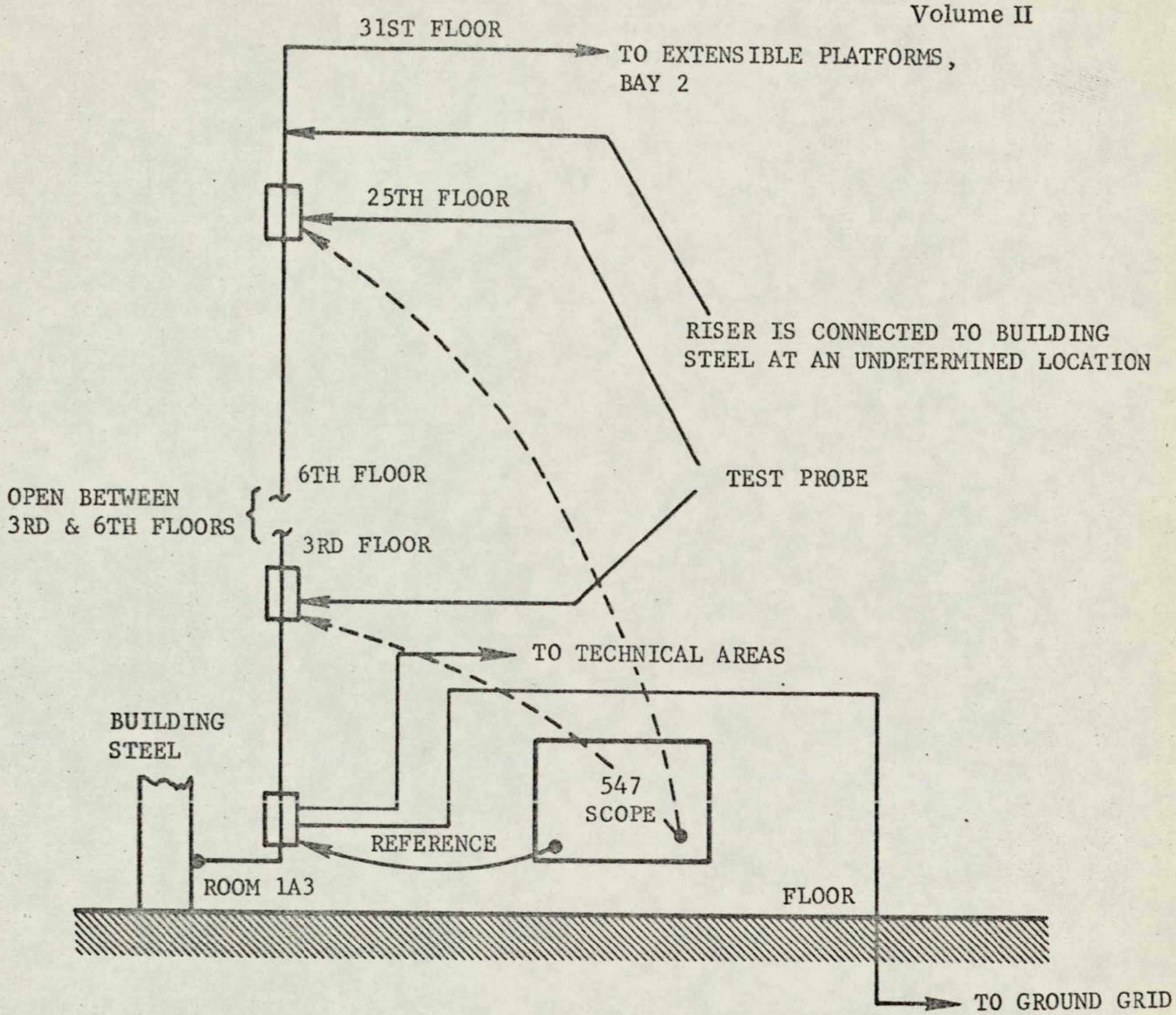


Figure 3-37 Noise Mapping Test Set-up for Tower A

the I-Ground plate is acting as a source of noise for this installation rather than as a noise sink and that building steel would provide a quieter ground reference.

The ambient noise voltages in the test probe were less than 1.5 μV as shown in Figures 3-42 and 3-43.

3.4.4 Launch Control Complex (LCC)

3.4.4.1 General. The noise mapping measurements in the LCC were made in Firing Rooms 1 and 3. The test equipment and equipment configuration was the same as that used at the VAB, i.e., 547 oscilloscope with plug-in units, Type L, 1L-5, 1L-10, and 1L-20. The I-Ground plate in Room 1P6 was used as the ground reference point.

Probe on I-plate in Room 26E7, referenced on I-Riser in Room 1E3.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Horizontal
0.20 mV/cm Vertical

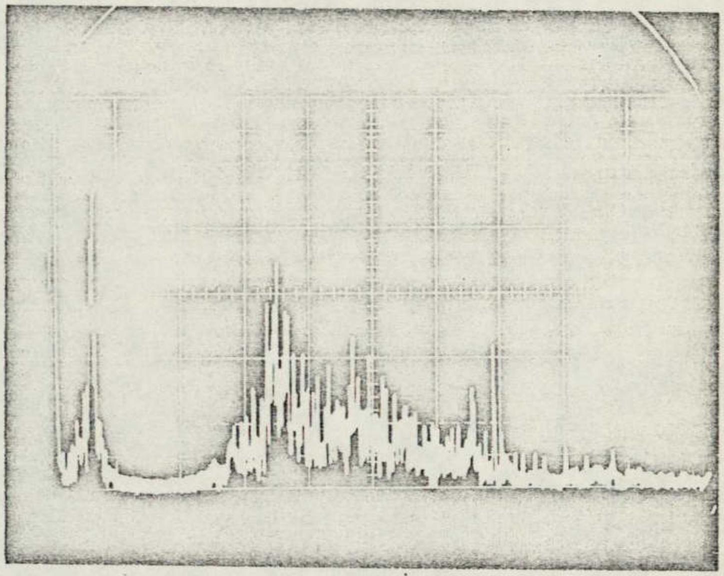


Figure 3-38 Noise Voltage in Frequency Domain, VAB Room 26E7

Probe on Rack 11 External Ground Stud, referenced on I-riser in Room 1E3.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Horizontal
0.20 mV/cm Vertical

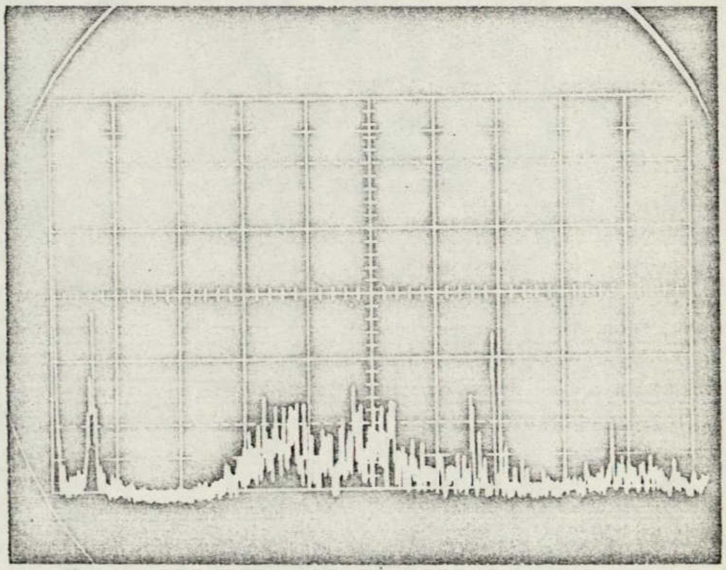


Figure 3-39 Noise Voltage in Frequency Domain, VAB Room 26E7

Probe on Ground Bus in Rack 12, referenced on I-riser in Room 1E3.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Horizontal
0.20 mV/cm Vertical

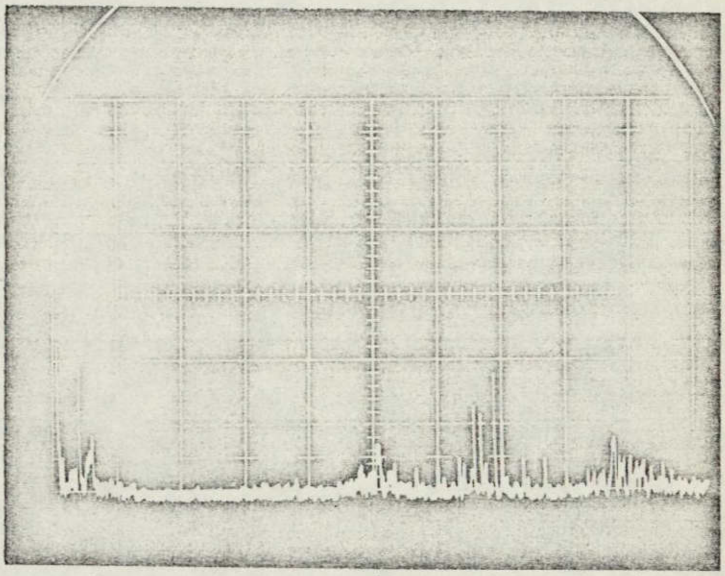


Figure 3-40 Noise Voltage in Frequency Domain, VAB Room 26E7

Probe on E-Ground Connections to Waveguide, referenced on I-riser in Room 1E3.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Horizontal
0.20 mV/cm Vertical

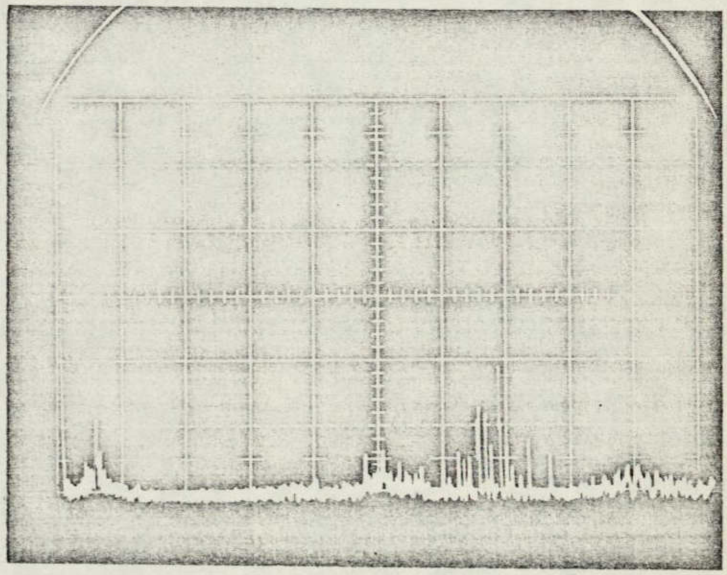


Figure 3-41 Noise Voltage in Frequency Domain, VAB Room 26E7

Probe open in Room 26E7, referenced on I-riser in Room 1E3.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Horizontal
0.01 mV/cm Vertical

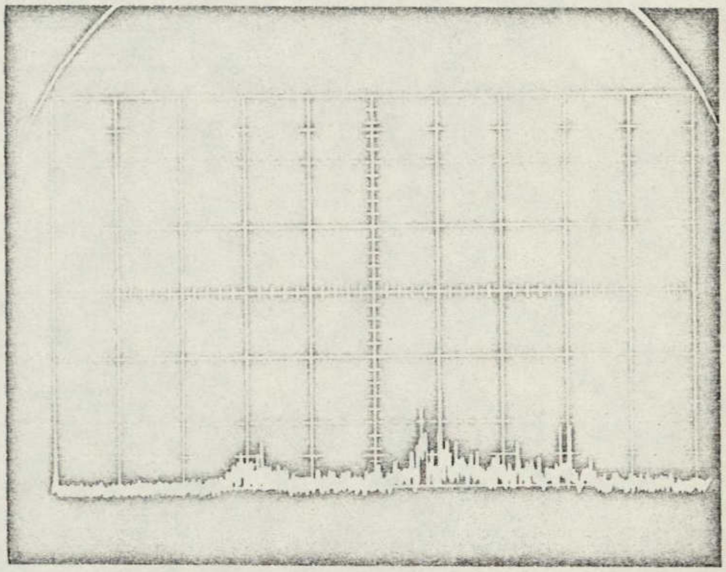


Figure 3-42 Noise Voltage in Frequency Domain, VAB Room 26E7

Probe in Room 26E7, Center Conductor connected to Shield, referenced on I-riser Room 1E3.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Horizontal
0.10 mV/cm Vertical

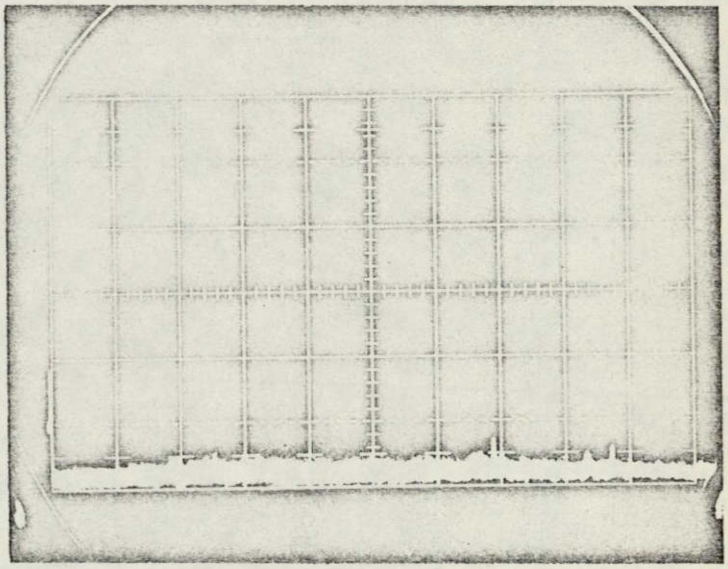


Figure 3-43 Noise Voltage in Frequency Domain, VAB Room 26E7

In general, the noise voltages observed in the 10-Hz to 1-MHz spectrum were less than 20 mV maximum for steady state condition. Occasional (random time interval) noise spikes of much higher amplitude and of short duration were observed during these measurements, but time constraints did not allow the time that would be required to monitor and measure them. NASA personnel that were present at the time of measurement stated that there is a history of noise pulses or bursts of unknown origin or cause. This particular problem should be given additional attention because it presents a probable source of degradation to control and communication functions.

3.4.4.2 Firing Room 3. Initial measurements were made in this room because it was in a down-mode condition and allowed the test crew to establish a measurement procedure without interferring with operations. It also provided an opportunity to establish the ambient noise levels in an environment in which the equipment was inactive.

The noise voltages that were observed during the measurements are illustrated in Figures 3-44 through 3-50. The most noticeable characteristics of these observations are the noise voltages appearing in the 200- to 300-Hz region of the spectrum measurements. The pattern of the spectrum was not constant but would vary in a random manner; the difference that can be seen in the illustrations is indicative of the range of variation.

Figure 3-49 is an illustration of the appearance of a time domain measurement of the voltage appearing at the same point at which the spectrum of Figure 3-48 was made, and Figure 3-50 is an extended view of the first noise spike that appears on the time domain waveform. The frequency of the waveform in Figure 3-50 measures approximately 250 kHz, which could in turn account partly for the noise voltages observed in the 200- to 300-kHz region of the noise spectrum.

3.4.4.3 Firing Room 1 Measurements. This room was in active support of the Apollo 13 mission at the time the measurements were made; therefore, it provided an opportunity to make observations in a dynamic operating enviroment. Noise mapping measurements were made using the same procedure as for Firing Room 3 and, as much as possible, at equivalent locations on the grounding system.

A study of the data for the two rooms shows that the noise voltage and frequency distribution of the noise on the two grounding systems is nearly the same despite the difference in their dynamic operating environments. Table 3-4 is a tabulated listing of the data for the two rooms. Figure 3-51 is a measure of the ambient noise within the test set. Figures 3-52 through 3-60 are illustrations of noise voltages that appeared on the grounding systems in this room.

The greatest difference in noise voltage is the signal ground pipe, which indicates that the noise level in the dynamic environment is 6.4 dB below the noise level in the inactive environment. Voltage amplitudes were observed to vary 6 dB or more during the measurement period and probably account for the apparent anomaly. The very low levels of noise observed indicate that the grounding system in Firing Rooms 1 and 3 of the LCC are adequate.

Probe on Signal Pipe in Firing Room 3. Reference on I-plate in Room 1P6.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Disepersion
500 ms/cm Horizontal
1mV/cm Vertical

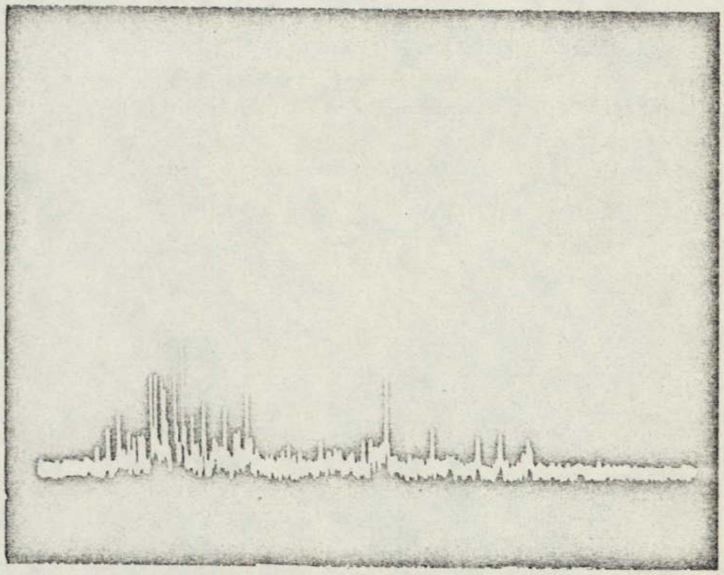


Figure 3-44 Noise Voltage in Frequency Domain, LCC Firing Room 3

Probe on Static Pipe in Firing Room 3. Reference on I-plate in Room 1P6.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Horizontal
1 mV/cm Vertical

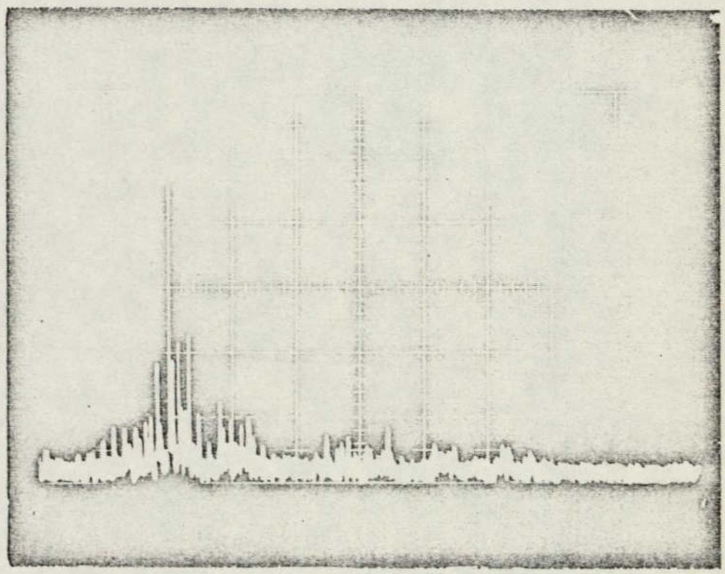


Figure 3-45 Noise Voltage in Frequency Domain, LCC Firing Room 3

Probe on I-plate in Firing Room 3. Reference on I-plate in Room 1P6.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Horizontal
2 mV/cm Vertical

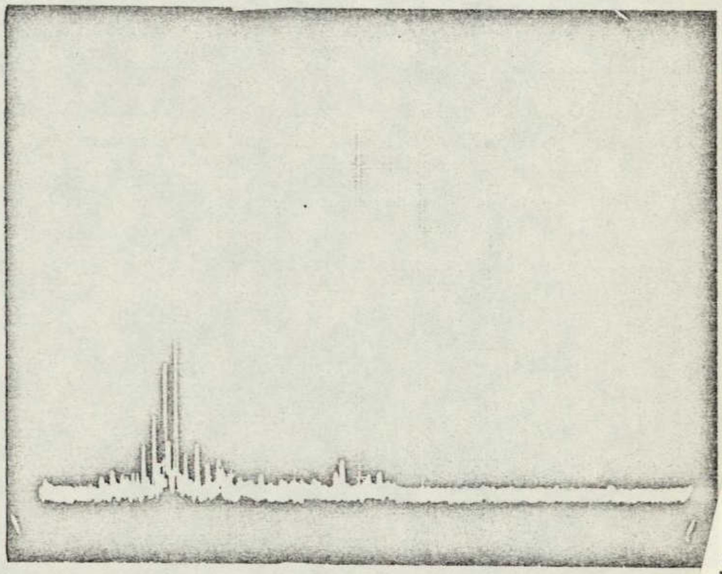


Figure 3-46 Noise Voltage in Frequency Domain, LCC Firing Room 3

Probe on E-Ground Grid Firing Room 3. Reference on I-plate in Room 1P6.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Horizontal
1 mV/cm Vertical

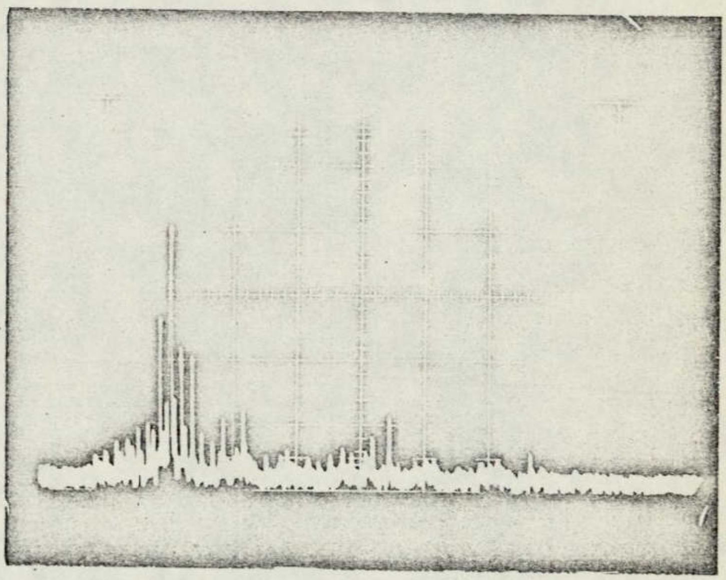


Figure 3-47 Noise Voltage in Frequency Domain, LCC Firing Room 3

Probe on 110 V, 60-Hz ac Power "Green" Wire. Reference on I-plate Room 1P6.

547 Oscilloscope

1L5 Plug-In, Linear Mode

500-kHz Center Frequency

100-kHz/cm Dispersion

50 ms/cm Horizontal

1 mV/cm Vertical

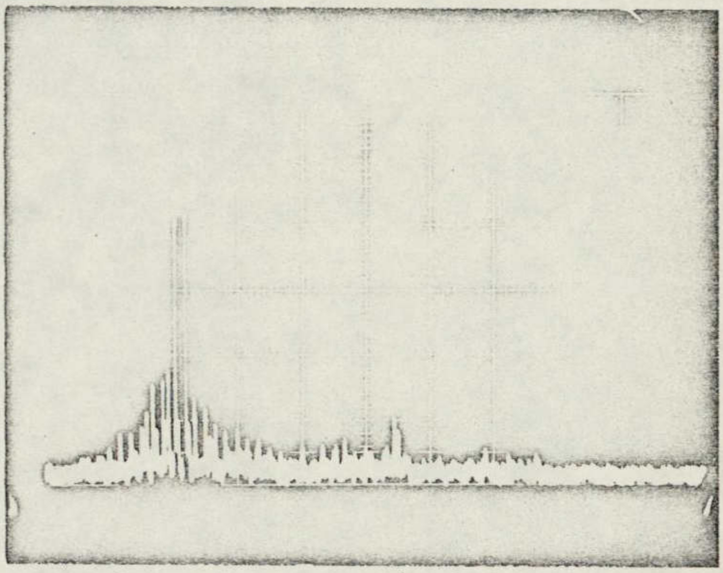


Figure 3-48 Noise Voltage in Frequency Domain, LCC Firing Room 3

Probe on 110 V, 60-Hz ac Power "Green" Wire. Reference on I-plate in Room 1P6.

547 Oscilloscope

1L5 Plug-In, Video Mode

2 ms/cm Horizontal

2 mV/cm Vertical

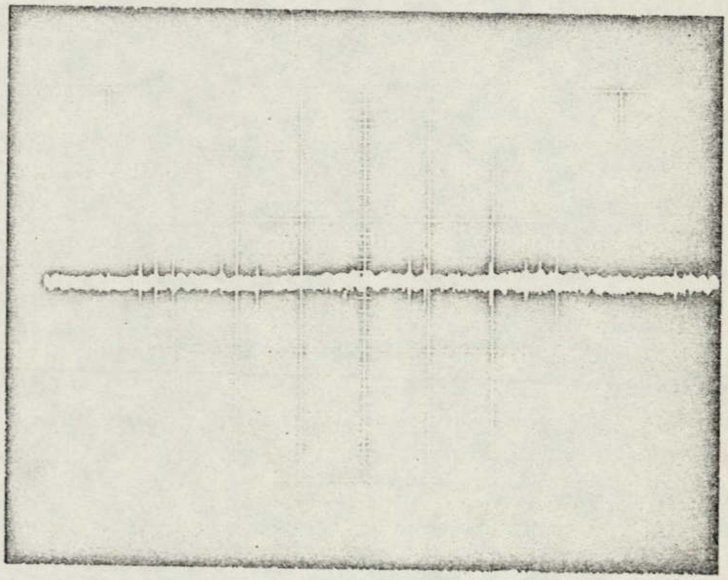


Figure 3-49 Noise Voltage in Time Domain, LCC Firing Room 3

Probe on 110 V, 60-Hz ac Power "Green" Wire. Reference on I-plate in Room 1P6.

547 Oscilloscope

1L5 Plug-In, Video Mode

10 ms/cm Horizontal

2 mV/cm Vertical

(NOTE: This waveform is the first noise spike of Figure 3-49 extended to show frequency characteristic.)

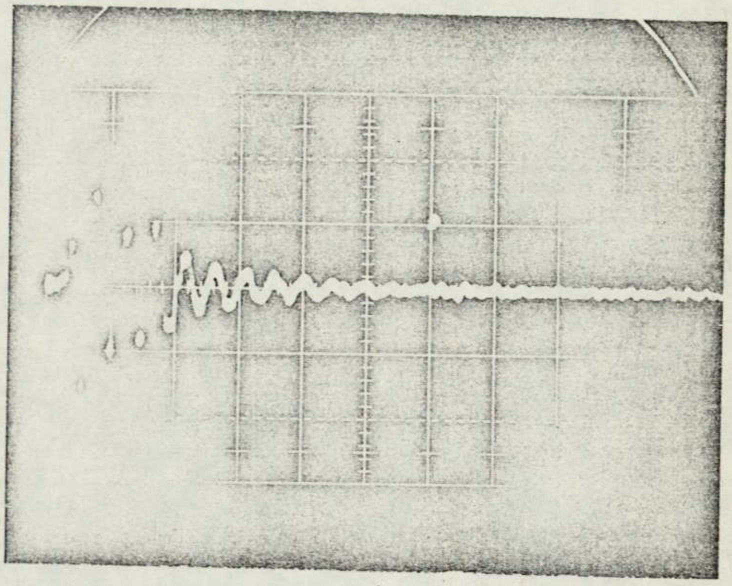


Figure 3-50 Noise Voltage in Time Domain, LCC Firing Room 3

TABLE 3-4

GROUND SYSTEM NOISE VOLTAGE COMPARISON
LCC FIRING ROOMS 1 AND 3

	Firing Room 1 (mV)	Firing Room 3 (mV)
I-Ground	5.8	4.6
Signal Ground	2.3	4.8
Static Ground	2.4	4.5
E-Ground	3.0	4.0

Probe open (no input) in Firing Room 11. Reference on I-plate in Room 1P6.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Horizontal
0.01 mV/cm Vertical

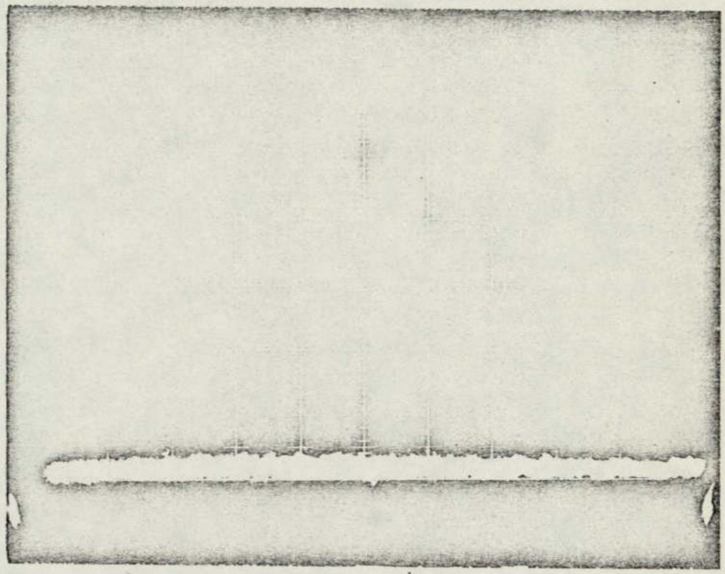


Figure 3-51 Noise Voltage in Frequency Domain, LCC Firing Room 1

Probe on I-plate near Room 3P13. Reference on I-plate in Room 1P6.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Horizontal
1 mV/cm Vertical

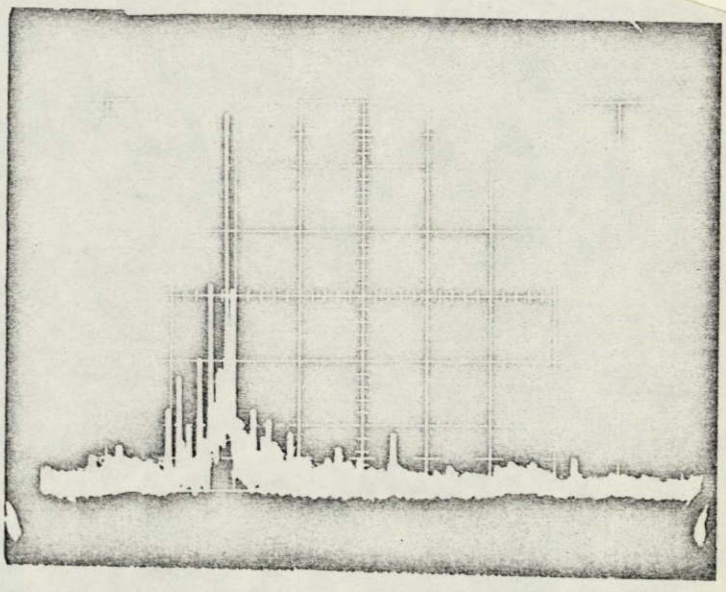


Figure 3-52 Noise Voltage in Frequency Domain, LCC Firing Room 1

Probe on I-plate near Room 3P13. Reference on I-plate in Room 1P6.

547 Oscilloscope
Type L Plug-In
2 ms/cm Horizontal
100 mV/cm Vertical

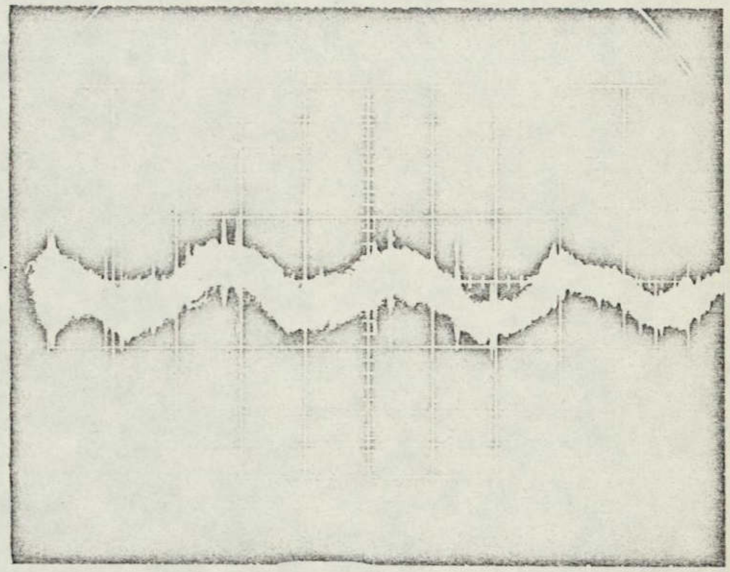


Figure 3-53 Noise Voltage in Time Domain, LCC Firing Room 1

Probe on Signal Ground Pipe near Room 3P13. Reference on I-plate in Room 1P6.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Horizontal
0.5 mV/cm Vertical

(First pulse is 1L5 zero reference pulse)

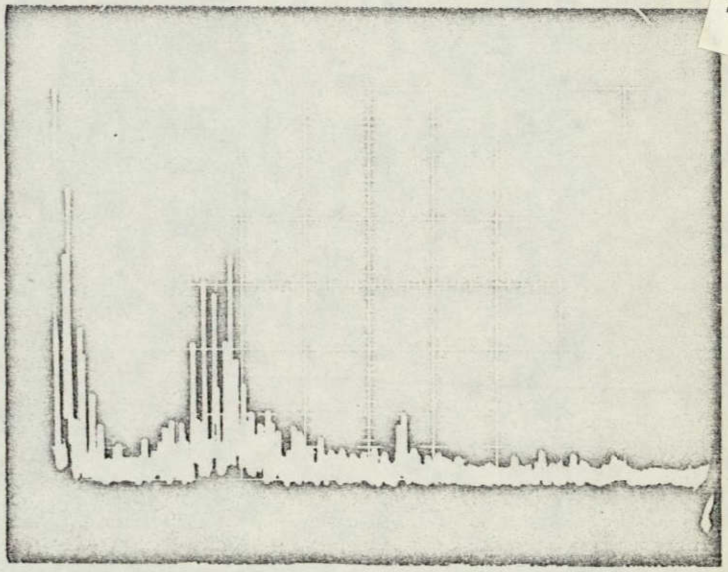


Figure 3-54 Noise Voltage in Frequency Domain, LCC Firing Room 1

Probe on Static Ground Pipe near Room 3P13. Reference on I-plate in Room 1P6.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz Center Frequency
50 ms/cm Horizontal
1 mV/cm Vertical

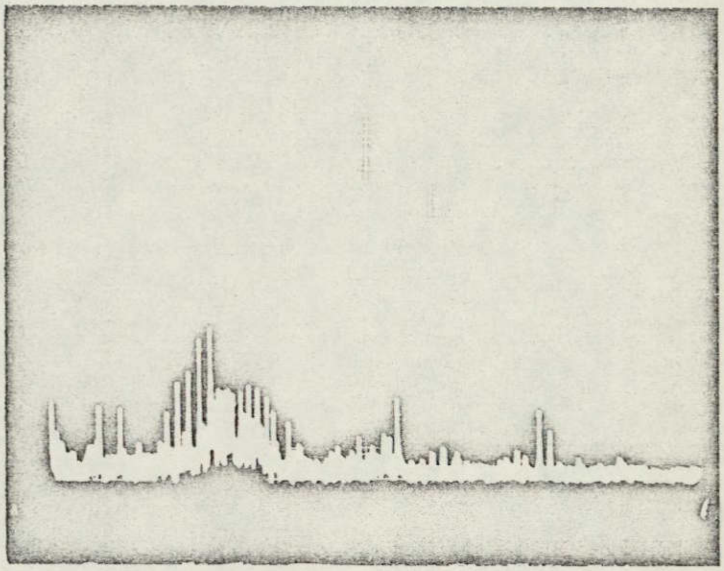


Figure 3-55 Noise Voltage in Frequency Domain, LCC Firing Room 1

Probe on E-Ground in Firing Room 1. Reference on I-plate in Room 1P6.

547 Oscilloscope
1L5 Plug-In
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Horizontal
0.5 mV/cm Vertical

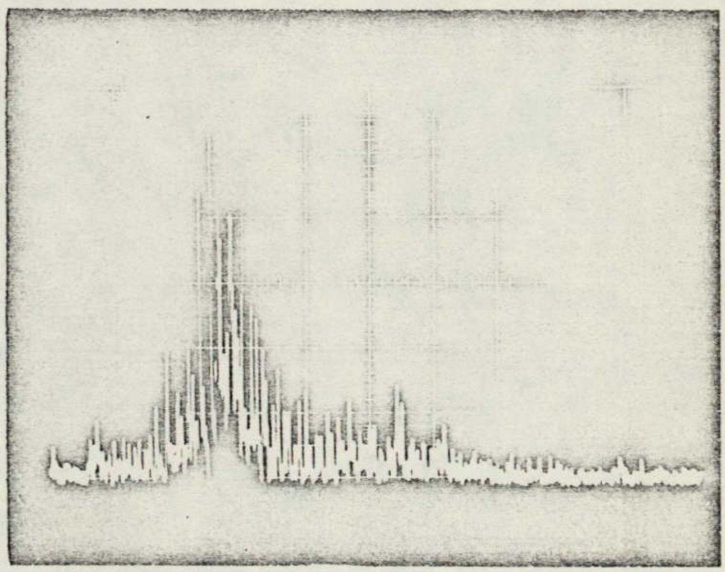


Figure 3-56 Noise Voltage in Frequency Domain, LCC Firing Room 1

Probe on E-Ground. Reference on I-plate in Room 1P6.

547 Oscilloscope
1L-10 Plug-In, Linear Mode
2.53-MHz Center Frequency
2-kHz/cm Dispersion
0.10 s/cm Horizontal
0.090 mV/cm Vertical

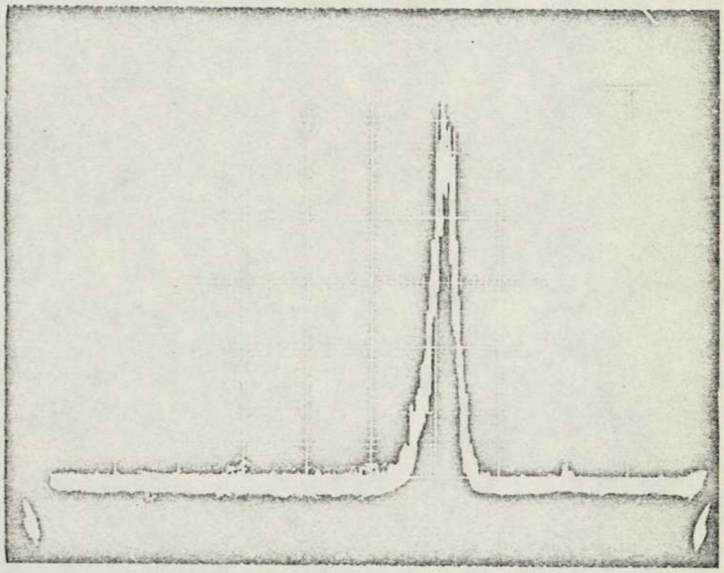


Figure 3-57 Noise Voltage in Frequency Domain, LCC Firing Room 1

Probe E-Ground. Reference on I-plate Room 1P6.

547 Oscilloscope
1L-10 Plug-In, Linear Mode
2.0 MHz Center Frequency
2 kHz/cm Dispersion
0.10 s/cm Horizontal
0.044 mV/cm Vertical

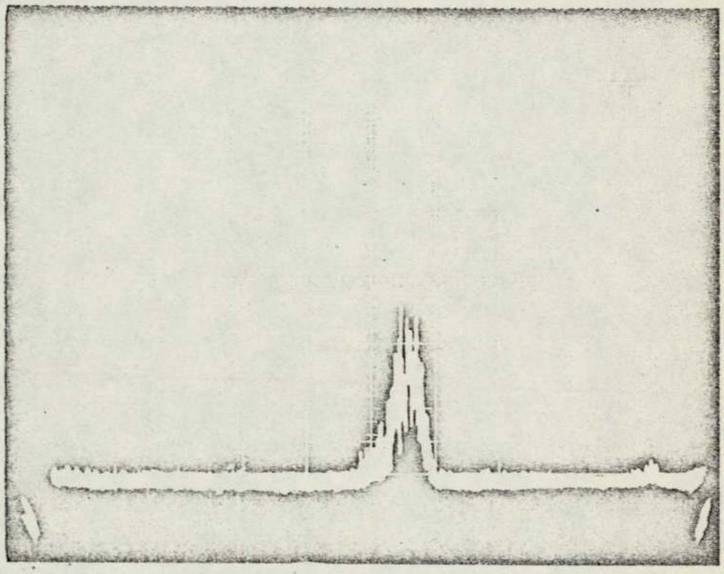


Figure 3-58 Noise Voltage in Frequency Domain, LCC Firing Room 1

Probe on I-Ground. Reference on I-plate Room 1P6.

547 Oscilloscope
1L-10 Plug-In, Linear Mode
2.0-MHz/cm Center Frequency
2-kHz/cm Dispersion
0.10 s/cm Horizontal
0.1 mV/cm Vertical

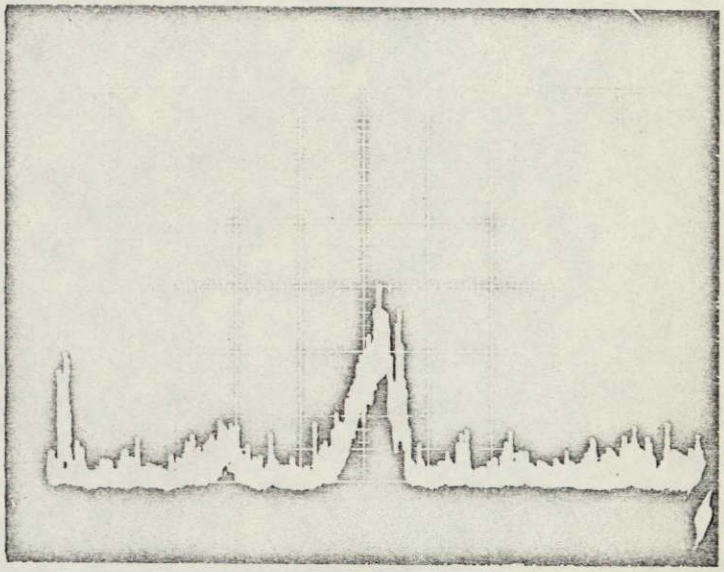


Figure 3-59 Noise Voltage in Frequency Domain, LCC Firimg Room 1

Probe on I-Ground. Reference on I-plate in Room 1P6.

547 Oscilloscope
1L-10 Plug-In, Linear Mode
1.62-MHz Center Frequency
2-kHz/cm Dispersion
0.10 s/cm Horizontal
0.013 mV/cm Vertical

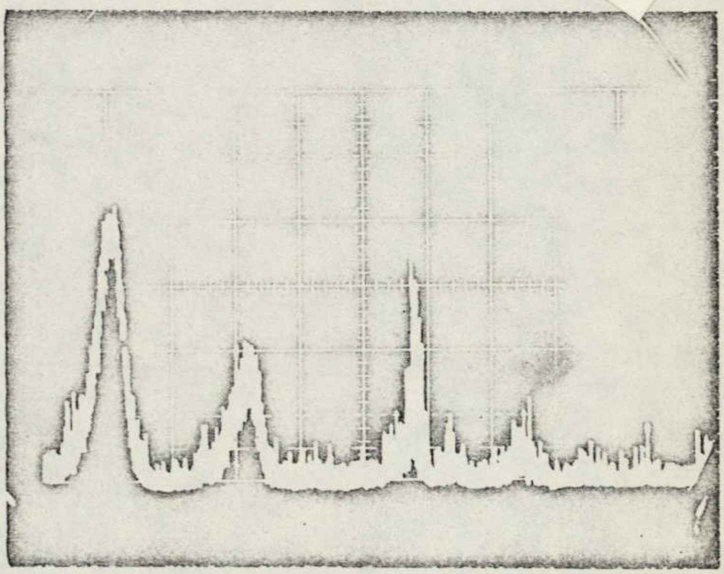


Figure 3-60 Noise Voltage in Frequency Domain, LCC Firing Room 1

Figure 3-53 shows that there is a 100 mV peak-to-peak, 60-Hz voltage, and 500 mV (0.5 V) noise spike on the I-Ground in this room. The noise spikes are of the same characteristic as those measured in Firing Room 3 (see Figure 3-57) but of a much higher amplitude (approximately 38 dB). The 500-mV noise spike is a high level of noise and could cause degradation of noise or pulse-sensitive equipment through inadvertent couplings in adjacent circuits. To avoid the possibility of this happening, the source of this noise should be determined and eliminated to the extent possible.

The 60-Hz component may be an indication of 60-Hz power imbalance to equipment that is tied to the I-Ground.

Figures 3-57 through 3-60 are illustrations of frequencies that were observed on the ground system in the frequency spectrum of 1 MHz to 35 MHz. The highest frequency observed was 2.532 MHz and the highest signal level was approximately 0.54 mV.

3.4.5 Manned Spacecraft Operations Building

3.4.5.1 General. The CURFCOE Room (3227) of the MSOB was the selected location for noise mapping in this facility.

3.4.5.2 Test Results. The noise voltages on the I-Ground bus were measured using both the building steel and the E-Ground bus as reference points. With the test configuration input connected to the I-Ground bus, where Rack 19 ground wires attach, and the reference test lead connected to the E-Ground bus, the 10-Hz to 1-MHz spectrum shown in Figure 3-61 was observed.

Distribution of noise voltages in this spectrum was fairly uniform to 950 kHz and did not change appreciably during several minutes of observation. At the time of measurement, the equipment in this room was on-line and in active support of the Apollo 13 mission; therefore, the ground system noise voltage contributed by this equipment would be at a maximum.

The average noise voltage is 150 μV, as can be seen in Figure 3-61. Noise voltages observed in the spectrum above 1 MHz that exceeded 20 μV are listed in Table 3-5. High amplitude, transient noise spikes did not appear during the period of observation.

TABLE 3-5

GROUND SYSTEM NOISE VOLTAGES IN EXCESS OF 1 MHz
IN MSOB CURFCOE, ROOM 3227

Frequency (MHz)	Microvolts Amplitude	Character
2.5	100	CW
5.0	20	CW
11.5	145	CW
15.5	200	AM with a 1-kHz modulation product on either side of carrier
37.5	160	CW
70.0	45	CW

When the reference test lead was connected to building steel, the 10-Hz to 1-MHz spectrum shown in Figure 3-62 was observed. The character of the spectrum is the same for the first measurement, but the amplitudes are approximately ten times or 20 dB higher. This indicates that there is 20 dB of isolation between the E-Ground bus and building steel at this point.

Mapping tests were not done in the ACE Rooms or the ACE Computer Rooms because of time constraints imposed by the test schedule and the LC-39 support schedules for Apollo 13. It is recommended that mapping measurements be done here to determine if the switching transients peculiar to operation of this equipment are of a magnitude that may degrade the operational quality of other equipment tied to the same grounding conductors.

3.4.6 LC-39 Pad A LUT 3

3.4.6.1 General. The noise mapping activities for this installation were confined to the ACE Room at the 280-foot level and Room 3AB of the LUT. Apollo 13 was in the start of FRT at the time of mapping measurements, so activity was confined to these two areas to reduce the time on the LUT to a minimum. Ground reference point was attached to the ground lead on the LUT pedestal jack nearest the PTCR.

The ACE Room structure on this LUT was bonded to the LUT steel structure by copper bonding straps that were brazed to LUT structural steel. The equipment in the ACE Room was grounded to the structure (E) ground; the I-Ground plates were installed but were not in use.

3.4.6.2 ACE Room Mapping. Figure 3-63 is an illustration of the 10-Hz to 1-MHz frequency spectrum observed with the test probe connected to the E-Ground in the ACE Room. The spectrum shows that the predominant spectrum of noise is in the 550- to 900-kHz range. The amplitudes of the various signals varied with time, but are typical of all measurements for the E-Ground in this area. Maximum voltage observed was 6 millivolts. Figure 3-64 is an illustration of the noise spectrum measured at the cable entry bulkhead.

Figure 3-65 is an illustration of the 10-Hz to 1-MHz frequency spectrum observed with the test probe attached to the I-Ground plate. The spectrum observed for this ground is shown in Figure 3-65, and it is interesting to observe the close similarity to the spectra for the E-Ground exhibit. If the intent of the I-Ground is to provide a ground network consistent with, but exclusive from the E-Ground, then the evidence shown here indicates that this intent may be violated by a compromise with the E-Ground.

3.4.6.3 Earth Ground Point (EGP), Room 3AB. The noise voltages present on the LUT EGP was measured to the pedestal ground point to determine the extent to which the EGP may be above earth reference. Figures 3-66 and 3-67 illustrate that the EGP was as much as 40 mV above reference at the time of measurement.

Two factors contribute to this voltage: the first is the noise voltage contributed by the equipment using the ground system which is considered to be endemic to the system, and second, the voltages induced in the 500 MCM cable connecting the EGP to the ground reference on Side 2 of the LUT. The ground cable is not enclosed in conduit; it traverses areas of high electrical noise environment and is parallel to the LUT main ac power feeders in Room 11AB.

Probe on I Busbar in Rack 19. Reference on E Bus in CURFCOE.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Horizontal
0.001 mV/cm Vertical

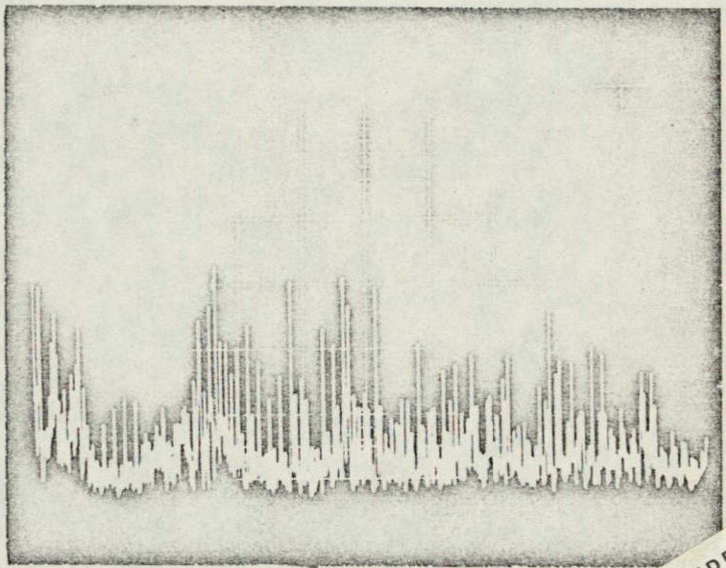


Figure 3-61 Noise Voltage in the Frequency Domain, MSOB, CURFCOE, Room 3227

Probe on I-Ground Bus. Reference on Building Ground in CURFCOE.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Horizontal
0.1 mV/cm Vertical

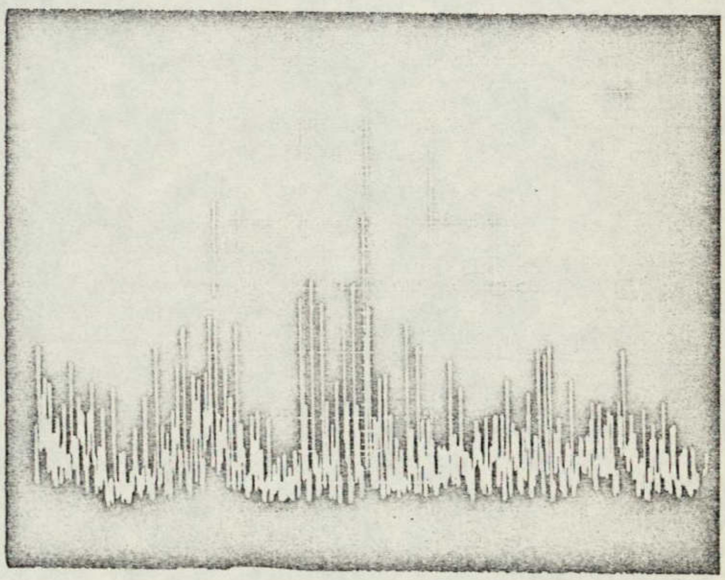


Figure 3-62 Noise Voltage in the Frequency Domain, MSOB, CURFCOE, Room 3227

Probe on E-Ground Plate. Reference on Pedestal Ground, Side 2.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Horizontal
1 mV/cm Vertical

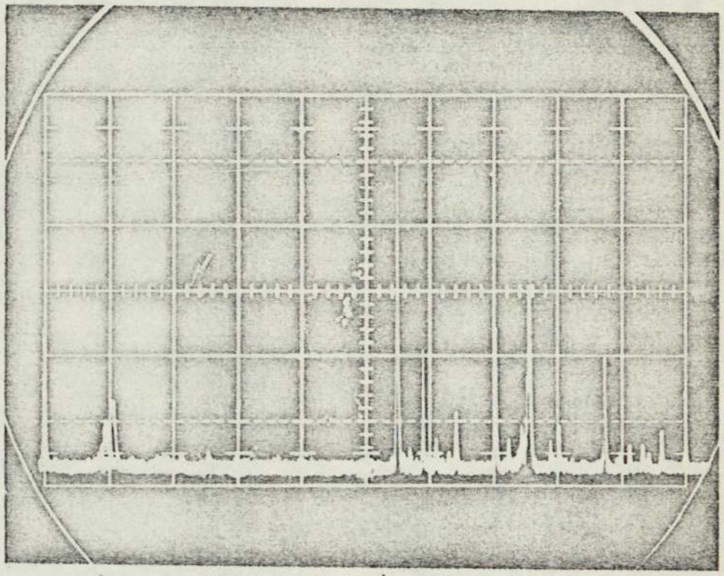


Figure 3-63 Noise Voltages in the Frequency Domain, LUT 3, ACE Room

Probe on Cable Entry Bulkhead. Reference on Pedestal Ground, Side 2.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Horizontal
1 mV/cm Vertical

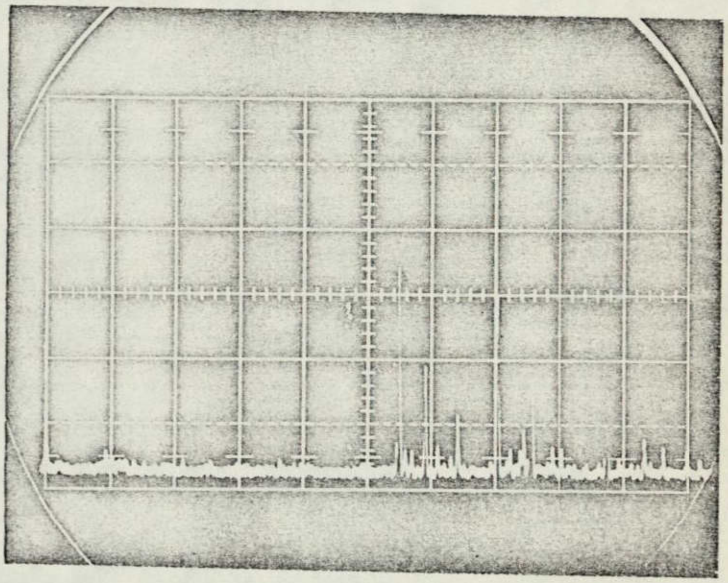


Figure 3-64 Noise Voltage in the Frequency Domain, LUT 3, ACE Room

Probe on I-Ground Plate. Reference on Pedestal Ground, Side 2.

547 Oscilloscope
1L5 Plug-In, Linear Mode
500-kHz Center Frequency
100-kHz/cm Dispersion
50 ms/cm Horizontal
1 mV/cm Vertical

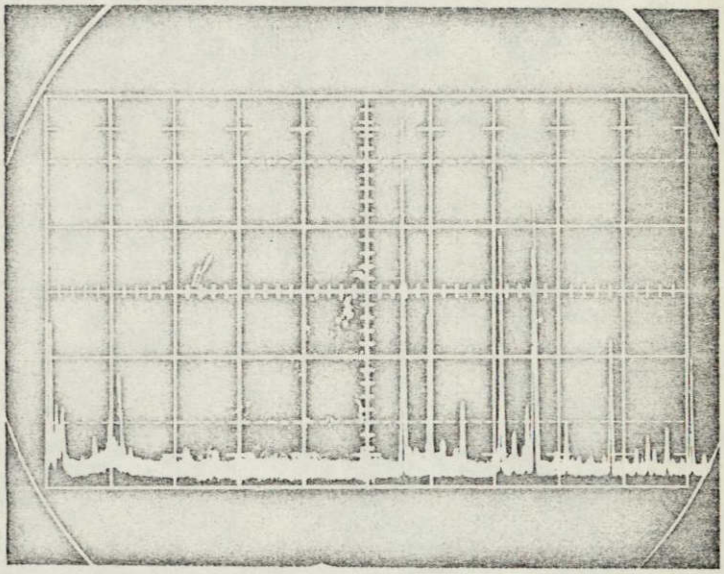


Figure 3-65 Noise Voltage in the Frequency Domain, LUT 3, ACE Room

Probe on EGP in Room 3AB. Reference on Pedestal Ground, Side 2.

547 Oscilloscope
1L5 Plug-In, Video Mode
2 ms/cm Horizontal
0.10 mV/cm Vertical

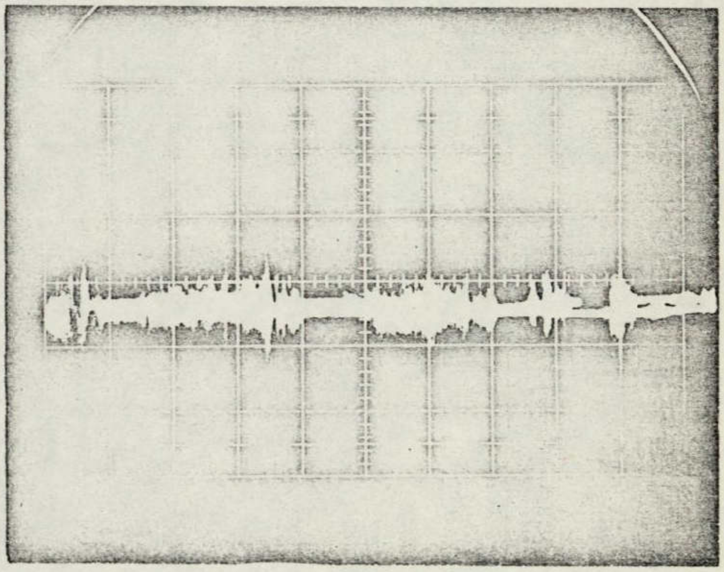


Figure 3-66 Noise Voltage in the Time Domain, LUT 3 EGP

Probe on EGP in Room 3AB. Reference on Pedestal Ground, Side 2.

547 Oscilloscope

1L5 Plug-In, Linear Mode

500-kHz Center Frequency

100-kHz/cm Dispersion

50 ms/cm Horizontal

0.5 mV/cm Vertical

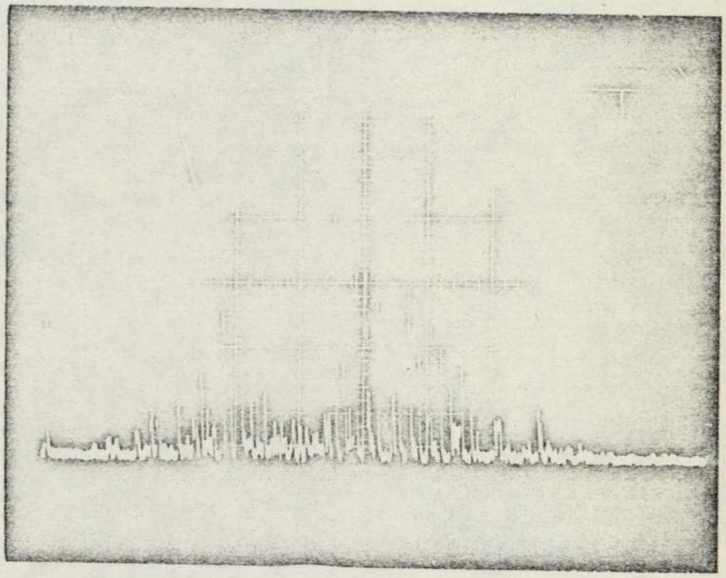


Figure 3-67 Noise Voltage in the Frequency Domain, LUT 3 EGP

At the time the measurements were made, there was no opportunity to isolate the ground lead to determine the amount of noise contributed by this source. In the interest of designing the grounding system to provide an EGP of lowest potential, this problem should be the subject of further investigation.

3.5 CONCLUSIONS AND RECOMMENDATIONS

3.5.1 General

The results of the total evaluation reflect that the basic bonding and grounding philosophy is, indeed, a valid one. Figures 3-68 to 3-70 illustrate good Zone 1 bonding practices observed during the inspection of LUT 2 and is illustrative of bonding in each of the towers. Figure 3-71 illustrates cable tray bonding practice used for bonding aluminum cable trays in the VAB. In general, the level of noise found on the various portions of the systems is relatively low. Only a few operational and performance problems can be related to grounding anomalies.

There are problem areas, however. One of these is the inconsistency in the manner in which the philosophy has been applied. This becomes particularly noticeable where additions have been made to the original installation. Quite frequently, these additions have resulted in compromise of the basic philosophy. Another concern is the lack of preventive maintenance or routine repair of portions of the grounding systems. A number of broken bonding straps, loose wires, and corroded grounding connections were noted. Figures 3-72 and 3-73 illustrate outdoor grounding connections that are not protected with protective coatings. Another apparent

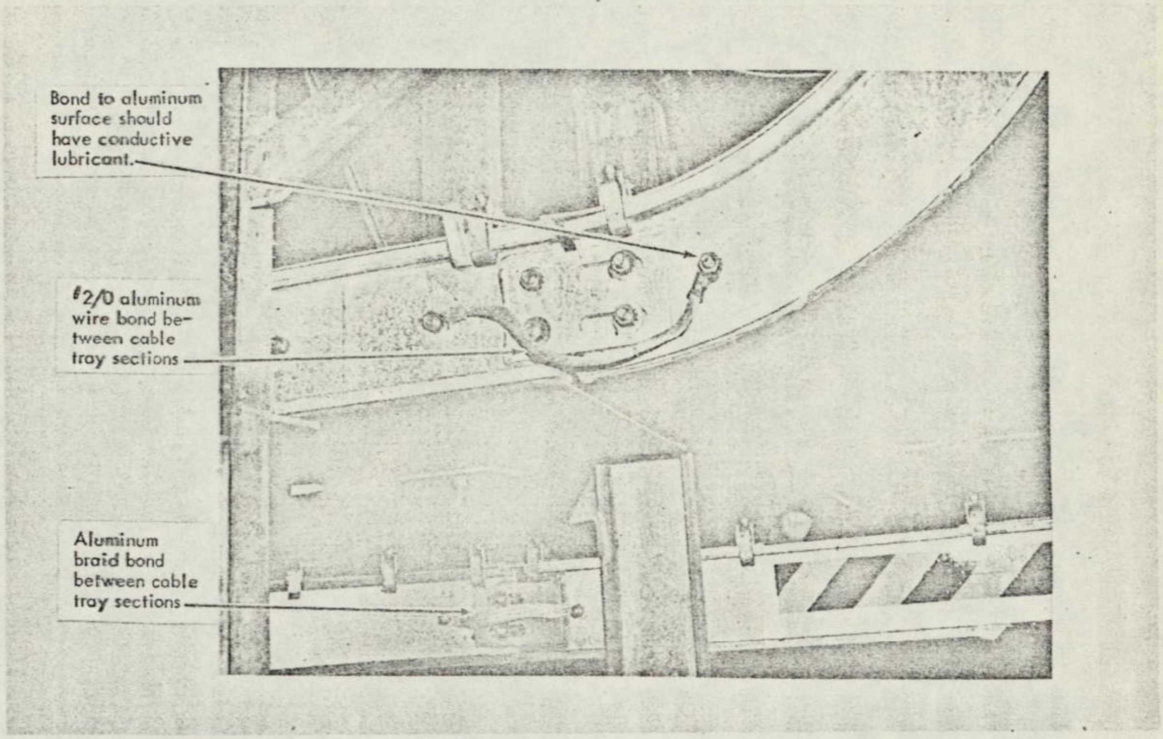


Figure 3-68 LUT-2, 240-Foot Level - Typical Cable Tray Bonding

Figure 3-69 LUT-2 - Typical Bonding in a Zone 1 Environment

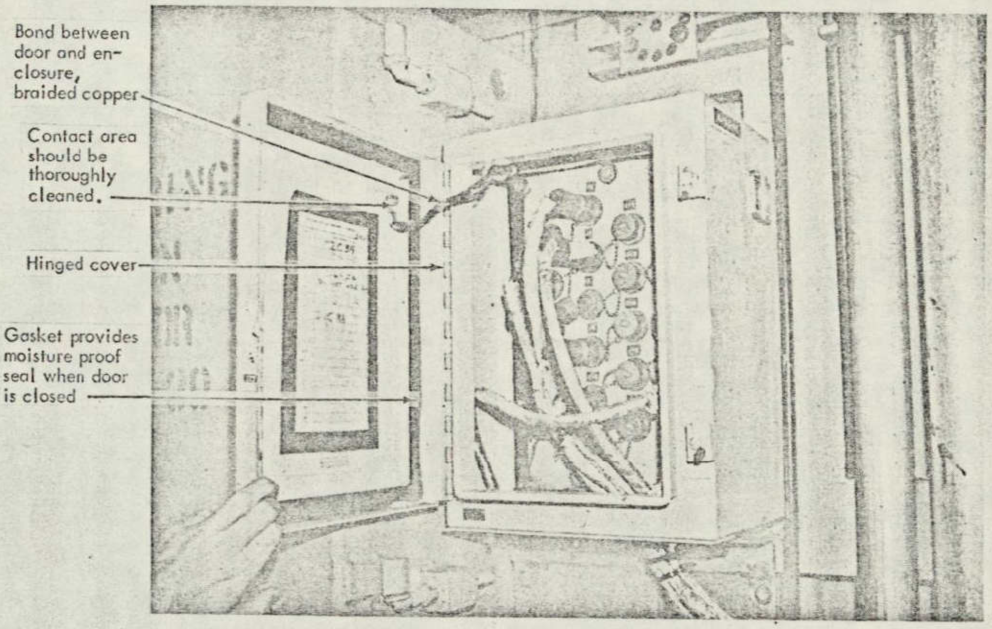


Figure 3-70 LUT-2 - Typical Bonding on Video Junction Box

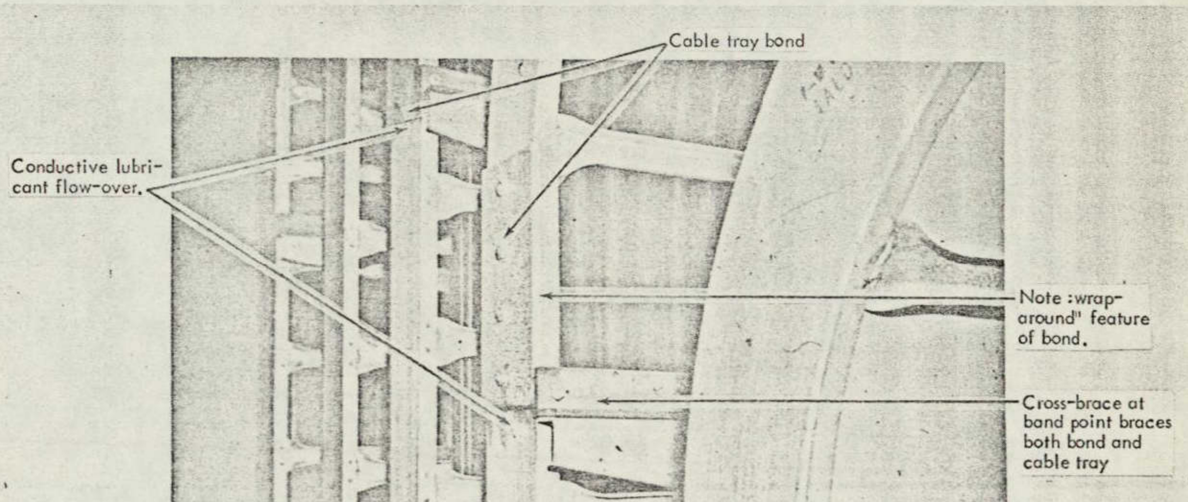


Figure 3-71 Typical Cable-Tray Bond in VAB. Note the use of conductive lubricant at aluminum joint.

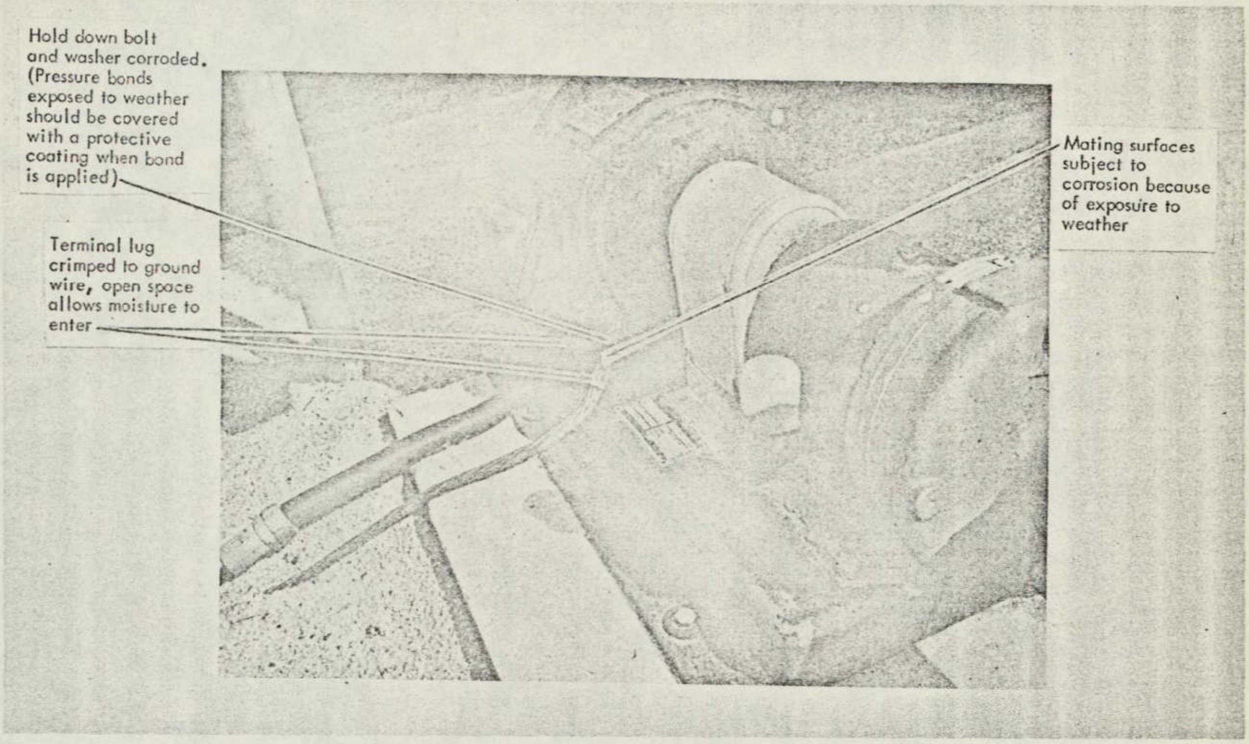


Figure 3-72 Outdoor Machinery Grounding. Note corrosion resulting from lack of protective covering.

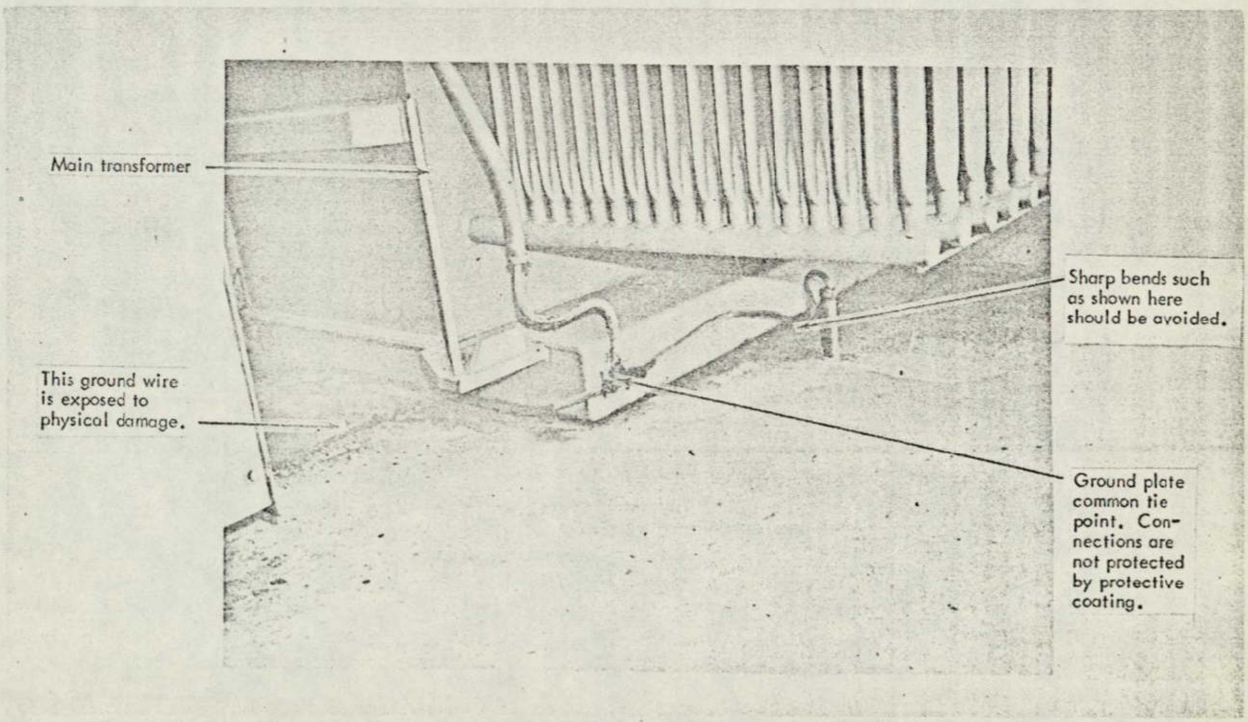


Figure 3-73 Typical Substation Power Ground (S/S 816). Note unprotected junction.

item is establishing an awareness of grounding requirements and precautions. This must begin at the level of providing labels and signs announcing to the nontechnical eye that this plate or that wire is a part of an active technical system, and disturbing it in any way could compromise the system. It must continue with developing a technical awareness in operating, installation, and maintenance personnel and, finally, engineering personnel. They must be aware of the technical "do's" and "don'ts" regarding the various grounding systems and bonding items. This development of grounding awareness has been accomplished with corresponding personnel in the USAF Satellite Control Facility with very gratifying results.

In the following paragraphs, some specific conclusions and recommendations will be delineated for the various areas of KSC, together with some general across-the-board conclusions and recommendations. These will be reflected in the final criteria produced for this project.

3.5.2 Vehicle Assembly Building

The following recommendations are made for the Vehicle Assembly Building:

- Install the missing portion of the I-Ground riser in Tower A.
- Locate and correct the E-to-I compromise above the sixth floor in Tower A.
- Reroute the OIS ground now running from Rooms 15B13 to 15B1A to run from Rooms 15B2 to 15B1A.
- Revise the rack grounding arrangement in Room 5D5 to eliminate the I-Ground compromise. The bare wire connection to the I-plate should be removed and the racks connected to E-Ground or building steel.
- Verify that the filters in the ground lead of the screen room (Room 1E21) are not in series with the I-Ground riser. The ground connection for the screen room should be connected to a grounding stud that penetrates the wall of the room.
- In Room 26E7, add eight neutral wires from the power panel to the equipment racks; each of the 12 loads should have a separate neutral wire. Provide RFI power line filters for the TWT modulator, TWT, and power meter.
- The I-Ground connection is not required for the RF racks in Room 26E7 and, accordingly, should be removed.
- A silver-soldered bond should be provided to connect the aluminum air terminals to the building steel.
- An air terminal should be provided to protect the exposed cable tray.
- The unused parabolic antenna with a broken air terminal should be removed.

3.5.3 Launch Control Complex

- In Room 2P10, the rack grounding should be improved by providing a copper busbar for connection of chassis grounds in place of the connections to the anodized rack upright.
- The racks in Room 2P10 should be insulated from the raised floor.
- The green wire connection in all racks in the LCC should be made to the rack ground and the extensions now connected to neutral or panel ground should be removed.

3.5.4 Launcher/Umbilical Towers (LUT's)

- In all LUT's, isolate and shield in conduit the 500 MCM cable from the ground point in Room 3AB to the outside ground point, from the power runs.
- Correct the E- to I-compromise in C14-267-1 at the LUT 280-foot level.
- Correct the E- to I-compromise in 514-121B and 14-053 at the LUT 80-foot level.
- Redesign the equipment racking arrangement in the ACE Room at the LUT 280-foot level to provide positive connection of both E- and I-Grounds.
- Provide a welded bond between the ACE Room and structure for all LUT's (under way). Figure 3-15 shows an ACE Room that is not bonded to structure.
- Revise LUT ACE grounding so C14-205 is not in series with the ground connections for other equipment.
- Provide a separate 500 MCM shielded ground reference for the LUT ACE Room.
- Provide welded bonds across the LUT swing arm hinges.

3.5.5 LC-34

- Redesign and implement the LC-34 grounding system to be consistent with the current grounding philosophy.
- Provide a more positive ground connection for the MSS (LC-34).

3.5.6 MSO Building

- Repair the intermittent I-Ground compromise in the MSOB-CURFCOE, Room 3227.

- Replace the surge protector on the MSO roof which is connected from the A-Ground to building steel.

- Provide an air terminal for the anemometer tower on the MSO roof.

- Provide elevated air terminals on the air conditioning duct to provide a cone of protection for the stile.

- Revise the air terminal wiring to include adequate bending radii, replacement of aluminum wiring, and provision of brazed or silver soldered connections.

SECTION 4

DEFINITION OF HAZARD ENVIRONMENT (TASK C)

4.1 GENERAL

4.1.1 Purpose

This task was undertaken to define the hazard environment at the J. F. Kennedy Space Center and its impact on the development of grounding and bonding criteria. Items considered were hazards to: (a) personnel, (b) mission sources and (c) equipment and facilities.

The hazard sources considered were electrical fault, lightning, explosion, EMI, and harmonic reradiation generated by nonlinear effects.

4.1.2 Scope

The outputs of this task are derived from a number of inputs, including KSC documents called out in the contract technical exhibit, NASA documents retrieved from literature search, ASCO TORS, interviews of KSC personnel, and from KSC facility inspections made under Task B.

4.1.3 Reference Documents

ASCO TOR-669(6540)-4	Lightning Protection and Prediction Techniques
NFPA 70	National Electric Code
NFPA 78	Lightning Protection Code
British Standard Code of Practice, CP326:1965	The Protection of Structures Against Lightning
IEEE 68C12 EMC	Environmental Interference Study Aboard a Naval Vessel, R. F. Elsner, M. J. Frazier, L. S. Smulkstys and E. Wilson, ITTRI
NAS10-3755, ITTRI Project E 6078	A Study of Non-Linear Mixing of RF Signals in Steel above 30 MHz
ITTRI E 6047-7	Study Concerning Non-Linear Mixing of RF Signals in Steel Structures
GE-ASD-RSIC-486	Memo on RFI Problems in Checkout of SA-5 Prevention, Detection, and Suppression of Hydrogen Explosions in Aerospace Vehicles

MIL-B-5087B — Bonding, Electrical, and Lightning Protection for Aerospace Systems

4.2 HAZARD SOURCES

The sources of hazard were generally defined in Paragraph 4.1.1 as electrical fault, lightning, explosion, and EMI. This section will define specific cases of the above and will weight these according to their severity.

4.2.1 Electrical Fault

Electrical fault hazard is that which can occur as a result of a voltage being applied to a device or structure as a result of an insulation failure or other inadvertent connection to a voltage source. This type of fault can result in shock hazard to personnel, electrical damage to equipment, and the generation of EMI and explosion hazard from arcing. It is difficult to assign a definite voltage level at which a fault becomes a hazard because of the many variables involved. A fault becomes potentially hazardous to personnel if a potential of 50 volts or greater appears on some exposed item with which personnel could come in contact. The voltage level at which damage could occur depends on the equipment involved and can range from the millivolt level to the kilovolt level. Arcing which will produce EMI and ignition of explosive materials can occur at voltages as low as one volt if the circuit internal resistance is low enough.

To provide fault hazard criteria which apply to the majority of the potential hazard conditions, consideration will be restricted to those hazards arising from faults in the primary ac supply. Such faults can occur in motors, equipment chassis, distribution panels, and, in the presence of condensation or excessive moisture from any source, in any device in which or through which the power is supplied. These faults can cause the power supply voltage to appear on the external surface of these devices, thus creating a shock hazard.

The usual procedure for protecting against shock hazard or equipment hazard resulting from such faults is the provision of a low impedance path to ground for the fault currents. This low impedance path will ensure that a large enough current flows to initiate rapid operation of the circuit protective device - fuse or circuit breaker. The National Electrical Code stipulates that such a protective grounding path shall not exceed 25 ohms resistance. This is inadequate to provide the required protection by effecting rapid operation of the protective device. With a 120-volt ac supply, the resulting fault current with a 25-ohm ground resistance would be, at the most, 4.8 amperes. This is inadequate to operate the protective device, which rarely is rated under 15 amperes. A criterion of return path impedance of 1 ohm will ensure operation of protective devices up to 100 amperes and is, accordingly, recommended for protection of personnel and equipment from electrical fault hazard.

Low voltage circuits, such as 28-volt relay circuits, must be included in this consideration. Faults in this type of circuit usually do not present a shock hazard other than the inductive surge when a relay circuit is broken. However, a fault occurring in these circuits can create an explosion hazard if it occurs in the appropriate atmosphere. Here again, the protective devices in the circuit shall be of

such rating as to carry the circuit in normal operation but to operate rapidly in case of a fault. Special precautions are required to contain the elements of the circuit where it appears in a potentially explosive environment.

4.2.2 Lightning

Careful consideration of hazards from lightning is required for the KSC area because of the high incidence of lightning in that area. Isokeraunic maps of the United States show this area to have an incidence of 70 to 90 thunderstorms per year during which lightning occurs. This is the highest incidence in the 48 adjacent states. The worst month is August, with a maximum of 22 and a minimum of 12 storm days.

There are two sources of hazard from lightning - direct strike potentials and strike-induced potentials. The former is produced by a direct strike on the structure involved and includes both the voltage of the bolt itself and the potential drops created in portions of the structure produced by the resulting current (10,000 to 100,000 amperes). The strike-induced potentials are caused by induction from the E- and H-fields of the bolt, and from potential gradients established in the ground by the dissipation of the lightning current. The ground gradient becomes particularly hazardous where cabling is installed between two points encompassing a sizeable potential gradient.

The lightning hazard is reduced by providing a low impedance path from a point where lightning is likely to strike to ground. Air terminals (or lightning rods) are provided which project above the structure to be protected. Such terminals connect to ground via a low impedance path. These air terminals serve two purposes. First, and of primary importance, they lessen the probability of a direct strike by providing a drain to the atmosphere of accumulated electrical charges. Second, if a strike actually occurs, they provide a low impedance path for draining current to the ground, thereby protecting the structure with which they are associated from severe damage. The connection from the air terminal to ground must be separate from that serving electronic equipment. The rationale for this separation is that the cable between the air terminal and the ground connection behaves as a transmission line terminated in a short circuit and, during a strike, high frequency energy in the bolt is reflected back to the air terminal. If the same ground connection were used for the lightning ground and instrumentation ground, the reflected energy might dissipate partially through the instrumentation ground, with resultant equipment damage.

The actual path which current from a lightning strike may follow is unpredictable and often its effects appear to be illogical. However, the provision of air terminals substantially lessens the probability of damage.

An additional feature of an air terminal is its so-called "cone of protection". The presence of an air terminal modifies the potential gradient between clouds and the earth in such a manner that a "cone of protection" is produced in its vicinity. The ratio of the height of the air terminal to the radius of the cone at ground level is 1:1 (Figure 4-1). Where two air terminals are adjacent, a 2:1 cone is achieved (Figure 4-2). Thus, all structures lying under this cone are protected. A good example of this is the LCC for LC-39 (Figure 4-3). Since the LCC lies within the cone of protection of the VAB, no air terminals are required on the LCC itself.

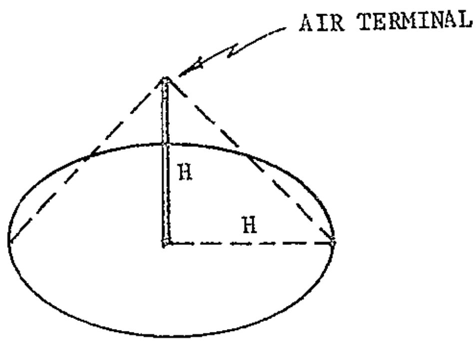


Figure 4-1 One-to-One Cone of Protection

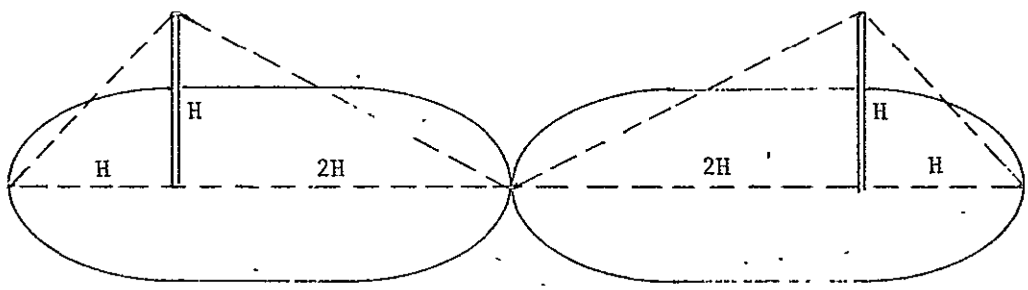


Figure 4-2 Two-to-One Cone of Protection

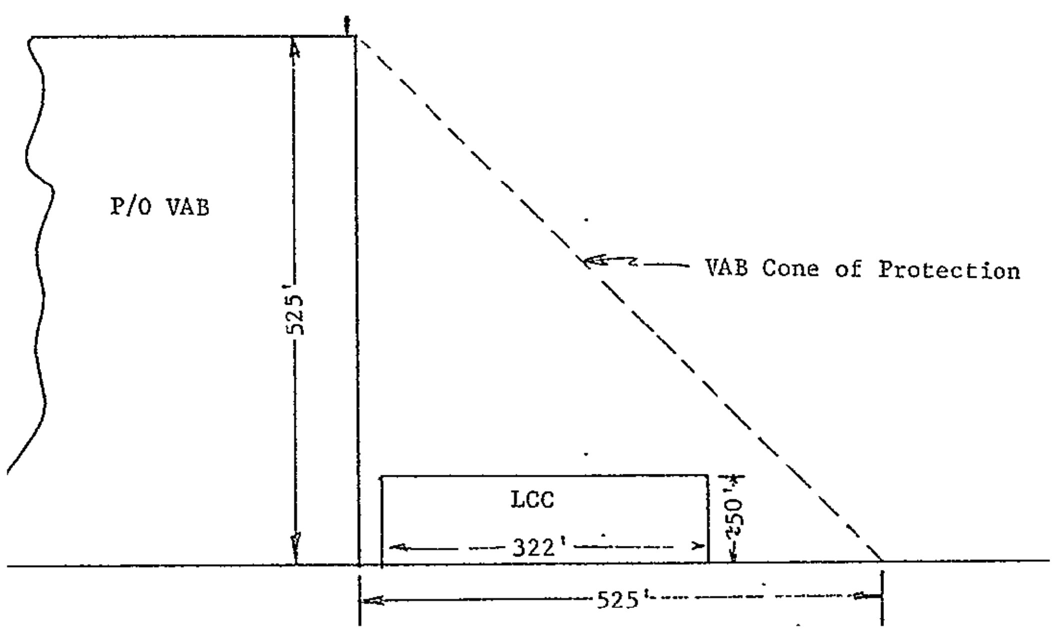


Figure 4-3 Lightning Protection of LC-39 LCC

4.2.3 Explosion Hazard

The vehicle servicing aspects of a launch complex inherently include a number of materials which, when combined with air or one another, form an explosive mixture ignitable by a spark. These materials and their hazard potential are as follows:

MATERIAL	EXPLOSION HAZARD
LOX (Liquid Oxygen)	When spilled in the vicinity of hydrogen or hydrocarbons, forms an explosive mixture.
LH_2 (Liquid Hydrogen)	When mixed with air in concentration of 4 to 74 percent by volume, forms an explosive mixture.
RP_1 (Refined Kerosene)	Flammable with air, explosive with LOX in a 1 to 5 percent mixture by volume.
Hydrazine (UDMH, MMH)	Flammable with air in concentrations of 2.5 to 98 percent by volume. Hypergolic with N_2O_4, IRFNA or HF. Explosive with spark or flame.
Solid Propellants	No explosion hazard except where EED might be initiated.

The quantities of these materials required for servicing the Saturn/Apollo vehicles are as follows:

QUANTITY
(pounds)

SA5 STAGE	LOX	RP1	LH_2	MMH	N_2O_4	Solid Fuel
S-I-C	3,306,630	1,431,540	---	Not Available		278
S-II	818,787	---	158,358	Not Available		604
S-IV-B	189,445	---	43,500	Not Available		59
	4,314,862	1,541,540	201,858	Not Available		941

These quantities require a sizeable plant for servicing. While the techniques for handling these fuels and oxidizers are highly advanced, there is a high probability that some leakage will occur. As a result of dispersion of facilities over a large area and generally prevailing winds, it is highly unlikely that concentrations of any of these materials of sufficient magnitude for explosion will accumulate. It has been shown in GE-ASD-RSIC-486 (Paragraph 4.3.1) that gaseous hydrogen in a concentration of 30% by volume in air can be ignited by a 5.5 microwatt-hour spark. The range of concentration for detonation is from 18 to 59% by volume, with higher energies required for other than 30% (30% is the optimum stoichiometric mixture). Energy levels of specified magnitude may readily be provided by electrical faults and lightning. It is highly unlikely that an RF signal resonating

on a piece of material of approximately half-wavelength will produce a spark of this energy level. This corresponds to a power density of about 2.4 megawatts/meter^2 and would be destructive to the structure itself.

4.2.4 EMI Hazard

EMI hazards in the LC-39 area are those which, by conducted or radiated interference, can jeopardize personnel safety, equipment safety, and mission success.

In the area of personnel safety, the EMI hazard of greatest concern is that of the biological effects on various tissues caused by radiated energy at frequencies in the SHF region. The greatest power level in this frequency band on LC-39 is 500-W ERP from the C-band beacon antennas. The biological "safe" level for this energy is 10 mW/cm^2 or 100 W/m^2. The power density at any point remote from an isotropic radiation is given as

$$P_t/4\pi R^2 \text{ watts/meter}^2$$

where

P_t = ERP in watts
R = distance from antenna

Rearranging to determine the safe distance yields the form

$$R = \sqrt{\frac{P_t}{4\pi P}}$$

where

P_t = 500 watts
P = 100 watts/meter^2

or:

$$R = \sqrt{\frac{5}{4\pi}} = \sqrt{0.4} = 0.63 \text{ meter}$$

Whenever personnel are within this distance of the beacon transponder antenna on the vehicle, the radiation "hats" are in place for closed loop testing. Accordingly, radiation hazard is negligible on LC-39.

Hazard to equipment from EMI sources alludes primarily to the effect of EMI on the operation of the equipment, although high EMI levels can physically damage such items as the sensitive front ends of receivers. Radiated and conducted EMI, if of sufficient magnitude, can interrupt the operation of many items of equipment. To combat these effects, a part of the systems design is dedicated to identifying potential sources of EMI and potentially susceptible devices within the system under consideration, as well as adjacent systems. The system designer then

delineates the precautions to be taken in the areas of grounding, bonding, shielding, cabling, and filtering to minimize the effects of EMI.

Of particular concern in this area is the accidental operation of electro-explosive devices (EED). Such accidental operation can result from two sources. The first is by accidental actuation of the proper command channels to initiate EED operation, and the second is by direct EMI action on the EED itself.

Coding techniques have been designed into the command system to preclude the accidental operation of the command channel from EMI. The codes are sufficiently long and are designed with enough check bits that the probability of accidental operation from an EMI source is 10^{-27}. In addition, an investigation of the sources of radiation in the KSC area reveals no combination of sum and difference frequencies or products that lie in the command frequency range.

EED's are usually placed well within the vehicle where they are inadvertently shielded by at least the vehicle skin. In addition, EED circuits are installed using twisted shielded pairs, thus further enhancing their isolation from EMI sources. EED's are required to not fire, dud, or deteriorate in performance with an applied energy of 0.15 joule.

Assuming a shielding effectiveness of 30 dB for the EED circuit installation (typical of twisted wire shielded) and neglecting any effect of the shielding effectiveness of the vehicle skin, an EMI energy level of 150 joules would not initiate the EED's. Assuming an equivalent cross section of 1 m^2, an EMI power density of 150 W/m^2 for 1 sec would not initiate the devices. At such a power level, however, the vehicle skin and structure would be vulnerable to damage from ohmic heating effects.

4.2.5 Harmonic Reradiation from Structural Members

4.2.5.1 Introduction. Under certain circumstances, structural members of building, tower, etc., will, if irradiated by an incident radio wave, generate and reradiate power at harmonics of the incident signal. This hypothesis has been subjected to detailed analysis[1] as well as experimental verification[2].

The previous analytical work on this subject, as verified by experimental measurements, suggests that harmonic reradiation is a serious cause of EMI signals in any area of limited extent containing considerable numbers of radio transmitting and receiving apparatus, such as those operating with the KSC Launch Complexes. This document explores certain aspects of harmonic reradiation from structural members, with particular emphasis on the computation of RF power relations between the incident fundamental frequency and reradiated harmonics.

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[1] A Study of Non-Linear Mixing of RF Signals in Steel above 30 MHz, IIT Research Institute, Final Report, Contract No. NAS 10-3755, IITRI Project No. E6078, 31 March 1967.

[2] Ibid, Section V, page 104.

It is concluded that reradiation of harmonics, especially the third harmonic, does in part occur whenever structural members of a building or tower are not solidly bonded together, but WDL analysis indicates that the power level of the reradiated harmonic is highly unlikely to be sufficient to pose a serious electromagnetic interference problem.

Two mechanisms have been suggested as the source of the harmonic power:

a. If two separate structural members touch, with a (rusty) oxide layer between, that layer can act as a semiconductor diode, and if any ac voltage appears across the junction, a periodic but non-sinusoidal ac current will flow through the junction and into the structural members. The current may be Fourier-analyzed into a series of harmonics, of which the third is found to be the strongest. This third harmonic current, flowing into the structural members (which behave as transmitting antennas), then acts as the driving source for the reradiation of third harmonic power.

b. A single ferromagnetic (steel) structural member possesses a nonlinear magnetization wave (B vs H). As the H field of the incident radiation varies sinusoidally, through Maxwell's curl equation, $\nabla \times H = i + j\omega D$, the nonsinusoidal variation of B gives rise to harmonic current components that drive the structural member as an antenna and cause radiation of harmonic power.

The WDL analysis reveals that both phenomena may in fact occur, but that both require the structural members to be irradiated by really enormous power densities, if harmonic power of significant levels is to be reradiated.

4.2.5.2 Analysis of Harmonic Reradiation

4.2.5.2.1 Harmonics from Magnetic Materials. Consider the point listed in Paragraph 4.2.5.1b, namely, that magnetization curves of known magnetic materials are nonlinear. Also note that the B vs H curve for structural steel is substantially linear, certainly for flux densities below about 2000 gauss, and only relatively slight departures from linearity are observed up to about 4000 gauss.

When a radio plane wave irradiates a surface, the tangential component of the magnetization vector H must remain continuous as one crosses the bounding surface. Thus, if steel is irradiated by a plane wave, the value of the H tangential just inside the steel equals the value of the H tangential just outside the steel (i.e., in air).

The power density of the incident wave is given by Poynting's vector, $P = E \times H^*$, which for a plane wave is equivalent to

$$P = E^2/\eta \tag{1a}$$

or

$$P = \eta H^2 \tag{1b}$$

where η is the characteristic impedance of free space, i.e., 120π, or 377 ohms.

Inside the steel the flux density B is related to H by the relation

$$B = \mu H$$

or

$$B = \mu_r \mu_o H \tag{2}$$

in which μ_r is the relative permeability of the steel, at the frequency of the incident signal, and μ_o is the permeability of free space; i.e.,

$$\mu_o = 4\pi \times 10^{-7} \text{ henries/meter} \tag{3}$$

For all known magnetic materials, μ_r is very strongly frequency dependent.

For cold-rolled or structural steel; μ_r may be substantial (200 to 500) at low frequencies, up to about 100 Hz; above this frequency, μ_r begins a steady decline, to a value only slightly exceeding unity for frequencies above 1 MHz.

Equation (2) may be substituted into Eq. (1b) to obtain a relation between the power density of the incident wave to the flux density in the steel; thus,

$$P = \eta B^2/(\mu_r \mu_o)^2 \tag{4}$$

Let us now substitute numerical values into Eq. (4), first arguing that the steel may be expected to behave in a nonlinear manner, and hence generate significant harmonic power --only if B is large enough (at the peaks of the ac cycle) to represent a substantial departure from linearity on the B-H curve. As noted above, such a value for structural steel is typically about 2000 gauss (0.2 Wb/m^2). Also, to consider the phenomenon at high RF frequencies, well above 1 MHz, we will consider that μ_r is only 2.

With these assumptions it is computed from Eq. (4) that:

$$P = \frac{(120)\,(0.2)^2}{\left(2 \times 4\pi \times 10^{-7}\right)^2} = 10^{13}\ W/m^2 \tag{5}$$

Now a radio signal as large as 1 W/m^2 is considered to be a very strong signal, and is unlikely to occur several miles from any known radio transmitter. (For example, if one radiates 100 kW with an antenna having 30 dB gain, the power density only 5 km away is about 0.3 W/m^2. To achieve densities of 1 to 10 W/m^2 requires more RF power, more antenna gain, or both (not impossible but also not likely to occur, especially in the Cape Kennedy complex.)

Thus, the computed power density, 10^{13} W/m^2, is many tens of decibels (130, to be specific) larger than one is likely to be able to produce. Any lesser power density simply will not drive steel far enough into magnetic nonlinearity to produce

noticeable harmonic generation. In fact, further analysis of this problem has revealed that if the irradiation power density is raised above 1 W/m^2, the structural member would melt (at moderate irradiation levels), or would vaporize (at higher levels) long before harmonic reradiation would be significant. Such radiation levels would also "burn" an ionized hole through the atmosphere well before vaporization of steel would be achieved.

4.2.5.2.2 Harmonics from Structures with Semiconductor Junctions. Let us now develop a formula for computing reradiated harmonic power from structural members which contain a semiconductor junction (i.e., a diode); to effect this calculation it is necessary to describe an electrical model of the irradiated system for use in developing the formulas.

The specific electrical model used for analysis consists of a slender conductor, into the center of which are inserted a pair of semiconductor diodes; the diodes are connected in parallel, in opposing polarities. This arrangement is shown in Figure 4-4.

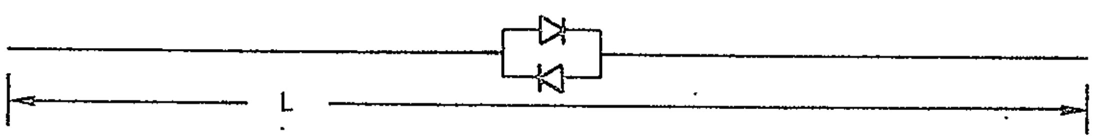

Figure 4-4 Simplified Electrical Model for a Structural Member

Such a slender conductor will act as a receiving antenna and will absorb power from an incident radio wave. This wave induces a voltage into the conductor; the induced voltage may be considered as applied across the diode terminals. If the diodes are considered to be semiconductor junctions, a current will flow through the diodes and into the conductor.

Now, the important characteristic of the model shown is that the diode current is a decidedly nonlinear function of the diode voltage. Hence, if the voltage induced into the system by an incident wave having a definite radio frequency f_o varies as $\cos(2\pi f_o t)$, the diode current will contain components at f_o and all its harmonics.

Consider that the length L of the system shown in Figure 4-4 is half a free-space wavelength at the frequency f_o. A half-wave antenna is an effective receiver for a suitably polarized incident signal with a relatively low terminal impedance (73 ohms)

at its center. The voltage V induced into a half-wave antenna by an incident signal of electric field strength E is given by

$$V = E\lambda/\pi \tag{6}$$

if the electric field is oriented parallel to the antenna.

At the second harmonic the antenna is a full wavelength long and the impedance at the center is very high, not conducive to the flow of much diode current. However, at the third harmonic the antenna is three half-waves long, the center impedance is relatively low (105 ohms), and the antenna is a very effective radiator. It is possible to show that the parallel arrangement of diodes shown in Figure 4-4 will not produce even-order current harmonics (if the diodes are a matched pair), and that the third harmonic current is by far the strongest harmonic for excitation of moderate or weak amplitude.

Thus, for the equivalent circuit shown in Figure 4-4, the predominant harmonic reradiation phenomena would appear to be:

a. Absorptoin of fundamental frequency power from an incident wave

b. The flow of third harmonic current through the diodes and into the antenna arms

c. Radiation of power, both at the fundamental frequency and at the third harmonic

It is meaningful to define a third harmonic scattering cross-section, A_{1-3}, which is the ratio of the third harmonic radiated power to the power density, or Poynting vector amplitude, of the incident signal. This cross-section is readily calculated as follows.

The peak fundamental voltage induced into the antenna is $V_o = E\lambda/\pi$. This voltage appears across the diodes and causes a current flow governed by the equation:

$$i = i_o \left[\exp(eV_o/kT) - 1\right] \tag{7}$$

If the tundamental voltage varies timewise as $V_o \cos(\omega_o t)$.

$$\begin{aligned} i &= i_o \left[\exp(eV_o \cos\omega_o t/kT) - 1\right] \\ &= i_o \left[a^2/4 + 3a^4/192\right] + i_o \cos\omega_o t \left[a + a^3/8\right] \\ &\quad + i_o \cos 2\omega_o t \left[a^2/2 + a^4/198\right] + i_o \cos 3\omega_o t \left[a^3/24\right] + \ldots \end{aligned} \tag{8}$$

where

$$a = eV_o/kT.$$

The third harmonic current is

$$i_3 = i_o a^3/24 \tag{9}$$

and the radiated third harmonic power is simply

$$p_3 = \frac{1}{2} i_3^2 Z_3$$

where Z_3 is the radiation resistance at the center of a $3\lambda/2$ antenna, i. e., 105 ohms; the factor 1/2 is required as i_3 is the peak value of the third harmonic current.

The amplitude factor i_o is evaluated by considering the dc current I_o passed by a diode under the influence of a dc voltage v_o, i. e.,

$$i_o = \frac{I_o}{\exp\ (ev_o/kT) - 1} \tag{10}$$

Hence,

$$p_3 = \frac{1}{2}\left|i_o a^3/24\right|^2 Z_3 = \frac{1}{2}\left[\frac{I_o}{\exp\ (ev_o/kT)-1}\right]^2 \left[\frac{eE\lambda}{\pi kT}\right]^6 \left[\frac{1}{24}\right]^2 \tag{11}$$

If v_o is small compared with e/kT, Eq. (11) may be expanded into powers of v_o, and only the lowest order term retained. This leads to

$$p_3 = \frac{(e/kT)^4}{1152\pi^6}\left[\frac{I_o}{v_o}\right]^2 E^6\lambda^6 \tag{12}$$

The amplitude of the incident wave Poynting vector P is equal to $E^2/120\pi$.

Consequently, A_{1-3} is given by $A_{1-3} = p_3/p$, or

$$A_{1-3} = \frac{5}{48\pi^5}\left(\frac{e}{kT}\right)^4\left(\frac{I_o}{v_o}\right)^2 E^4\lambda^6 \tag{13a}$$

or

$$A_{1-3} = \frac{1500}{\pi^3}\left(\frac{e}{kT}\right)^4\left(\frac{I_o}{v_o}\right)^2 p^2\lambda^6 \tag{13b}$$

Equations (13 a, b) show that the scattering cross section A_{1-3} is proportional to the 4th power of the incident field strength, or the square of the incident power

density, and also proportional to the 6th power of the wavelength. In UHF and microwave, the wavelength λ is so small that A_{1-3} usually is determined to be quite small.

As a numerical example, consider the incident radiation to be 450 MHz, $P = 1\ mW/m^2$, ($\lambda = 2/3\ m = 66.7\ cm$) (a fairly strong incident wave), and the diodes pass 50 mA (I_0) with one volt applied (v_0). Then, since $e/kT = 40$, if $T = 290°K$, $A_{1-3} = 0.026$ square meter.

Since the incident power density is 1 mW/m^2, the third harmonic reradiated power is: $1 \times 0.026\ m^2 = 26\ \mu W$.

4.2.5.3 Conclusion. Although the nonlinear junction mechanism can and will cause some harmonic radiation, an incident signal must be very strong for the effect to be significant.

The gross nature of the analytical models discussed above is fully recognized. Nevertheless, these models are adequate to indicate orders of magnitude and, in particular, to show that only unusually strong incident waves will produce significant harmonic radiation.

4.2.6 Summary

The hazard environment, its potentially damaging effects, and means of protection are summarized in Table 4-1.

4.3 OBSERVED HAZARDS

Close scrutiny of the LC-39 facilities and equipment revealed that, in general, the hazard environment has received careful attention and only minimal hazards exist. These are discussed in the following paragraphs.

4.3.1 Hazard from Electrical Fault

Only one potential hazard from electrical fault was observed in the VAB, Room 26E7. The conduit containing the ac power leads for the electronic equipment in this room became noticeably warm when the equipment was in operation. Further investigation indicated that 12 circuits were being supplied for these loads. These loads were served by only four No. 12 AWG neutral wires, which were the source of the heat. The hazard lies in the possibility of the insulation deteriorating to the point where a fault could occur. The resistance from the point of possible fault to the power ground on the building steel is a few milliohms and, accordingly, rapid operation of the circuit breakers is ensured. Therefore, no hazard to personnel exists. There is, however, a potential hazard to mission sources in that the IU checkout equipment in the room would be out of service until the source of the trouble was determined and corrected. Mission schedules could be jeopardized.

TABLE 4-1

HAZARD ENVIRONMENT CRITERIA

Hazard	Potential Damage	Protection
Electrical Fault	Personnel Shock	Low impedance ground path. Fast operate protective devices.
	Equipment Damage	Protective device rating near normal operating level.
	Explosion Hazard	All of above plus adequate containment.
Lightning	Personnel Injury	Air terminals for cone of protection in working areas. Low impedance path to ground. Isolation of potentially hazardous points.
	Equipment Damage	All of above plus minimizing potential sneak paths (ground and power circuits). Protective devices (surge protectors).
	Explosion Hazard	Cone of protection for areas having explosive materials. Static line cone of protection for lines.
Explosion	Personnel Injury	Discipline and strict access and safety rules.
	Equipment and Facility Damage	Provision for adequate dispersion of materials.
	Jeopardy of Mission Sources	Fault and lightning protection as above.
EMI	Personnel Radiation Injury	Restriction to within hazardous distance. Shielding of source during test (closed loop)
	Interference with Test/ Launch	Frequency selection. Control and isolation of source.
	Radiation from Nonlinear Junctions	Grounding and bonding of potential junction. Frequency selection.

4.3.2 Lightning Hazards

Several lightning hazards were noted during the site evaluation effort. These were noted in the report on Task B and are reiterated here as follows:

VAB Roof

- Aluminum air terminals have been used and are clamped to steel uprights. In the KSC environment, the dissimilar metal problem is severe. High resistance connections and potential noise sources can result from this combination.

- One section of cable tray extends above the cone of protection of any nearby air terminal.

- The air terminal is broken off one of the parabolic reflectors. Although this reflector is no longer in use, it remains a hazard.

VAB Towers A, B, and F

- Direct connection is made between building steel and the I-Ground.

LC 34

- The lightning ground for the MSS in both of these structures is connected through a metal shoe bearing on the transporting rails. This connection is an unknown and can have a high resistance. A positive connection should be provided. (This also applies to LC-37.)

- No air terminal is provided on the LOX facility.

- The air terminal provided on the LH_2 Dewar is inadequate. It appears to be an auto antenna

MSO Roof

- An inferior surge protection is installed between the A-Ground and building steel.

- No air terminal is installed on the anemometer tower. It appears that one bus had been installed and has broken off.

- A stile stairway across a large air conditioning duct is not within the cone of protection of any air terminal.

- Aluminum air terminals have been provided with aluminum cables connected to building steel. All connections are messenger clamps, some of which are loose.

- Sharp bends have been made in the aluminum cables to the air terminals. The minimum allowable bending radius is 8 inches.

CIF Building Roof

- No air terminals have been installed for the protection of the many antennas installed on this building.

4.3.3 Explosion Hazards

No explosion hazards were noted, with the possible exception of one which could occur as a result of the deficiency in protection from lightning of the LC-34 LH_2 facility.

4.3.4 EMI Hazards

No EMI hazards were noted in the external environment. The only hazards were potential hazards to mission success through conducted interference within the internal environment. An example of this is the incapability of the RF power meter in Room 26E7 of the VAB to be set to zero. This defect results from EMI conducted from the TWT modulator unit. Other examples of this may exist but were not detected because of time limitations.

4.3.5 Accident and Discrepancy Reports

A review of the accident and discrepancy reports on site by the contractor (Philco-Ford) revealed that no specific reports that dealt with EMI or grounding problems could be found.

SECTION 5

DEFINITION OF AREAS REQUIRING CORRECTIONS (TASK D)

5.1 GENERAL

5.1.1 Purpose

This task weighs the results of the on-site evaluation and the definition of the hazard environment versus the integrated standards and practices reviewed during Task A and from this weighing process defines corrections required in current grounding and bonding practice. In addition, specific site problems where corrective action is required are pinpointed.

5.1.2 Scope

This task record includes a brief rationale for the recommended correction. There is some redundancy between this record and those of Tasks B and C in that some of the same recommendations are included. The standards impacted by this report include the following:

KSC-STD-E-0012	Bonding and Grounding
KSC-STD-E-0013	Lightning Protection
DTI-E-9	Terminating and Grounding Shields in LF Instrumentation Cables

5.2 CORRECTIONS REQUIRED IN BONDING AND GROUNDING PRACTICES

5.2.1 General

The most general comment to be made regarding existing practices is that they are too general. They use expressions such as "as low as possible", "low enough to prevent" and "minimize the impedance" in describing standard practices. Instead, these practices should state definitive quantities, accompanied by suitable rationale. Other comments to be made would extol the virtures of consistency. A number of inconsistencies have been observed during the review of the practices. For example, the "cone-of-protection" afforded by an air terminal is defined as both 60° and 45°. Specific comments are covered in the following paragraphs.

5.2.2 Comments on KSC-STD-E-0012, Bonding and Grounding

The comments in this paragraph are related to specific paragraphs in KSC-STD-E-0012.

- Paragraph 1.2.1 states that internal bonding and grounding requirements are not covered. These should be covered as well as between a unit

and its environment. The standard, if it is to be effective, must cover all facets of a system.

- Paragraph 1.2.2 again restricts the scope of the practice to safety of personnel and equipment. Here again it is felt that a more catholic approach is needed.
- Paragraph 1.2.4, EMC Control Design, states that design to meet EMC requirements at equipment level is the responsibility of the equipment designer. However, the practice offers no guidance to these designers.
- Reference documents should include NFPA78, Lightning Protection, even though it is a bit redundant with KSC-STD-E-0013.
- Paragraph 3.1.1 is, again, apologetic for its limited scope.
- Paragraph 3.1.2.2 does not stipulate the required impedance in the definition of counterpoise. This impedance should be stated
- Paragraph 3.1.2.3 does not include the cathodic protection system and its ramifications in the definition of "Facility Ground Network".
- Paragraph 3.1.2.4 should indicate that the instrumentation ground should be connected to the facility ground at one point because of the noise from the cathodic protection circuit which is present on the building steel.
- Paragraph 3.2.2.7(c) speaks of the dimensions of the zero signal reference plane, that it should not exceed 1/20 of the wavelength of the highest frequency. This needs clarification as to the exact definition of the zero signal reference plane and its dimensions.
- Paragraph 3.2.2.7(d) stipulates that digital equipment should have a separate connection to the grounding network than analog equipment. This should be examined from a cost tradeoff standpoint.
- Paragraph 3.4.2.1 should stipulate that electrical power systems shall be grounded at one point only.
- Paragraph 3.4.3 should include some rationale for the dimensions given and rules for their measurement, i.e., along the longest side or whatever the intent is.
- Paragraph 3.5.2.1.4 should stipulate the requirements of the surface to which a clamp is attached.
- Paragraph 3.5.3.1.6 should include a table of tightening torques for various sizes of bolts.
- Paragraph 3.5.2.3 should stipulate the solvent to be used together with a caution note if any hazard to personnel is involved as, for example, in the case of carbon tetrachloride. It should also stipulate that the bond

should be made as soon after cleaning as possible to preclude the formation of oxides in the bond location. Paragraph 3.5.2.3.2 gives a time of 48 hours. This is too long, particularly if aluminum is involved.

- Paragraph 3.5.2.5 requires further clarification.
- Paragraph 3.5.2.6 should state that a bond should not affect the dynamic properties of moving systems. Torquing requirements for bolted bonding straps should also be stipulated.
- Paragraph 3.5.2.7 needs further clarification of "interval".
- Paragraph 3.5.2.13 should include a specific lubricant type such as "Eccoshield SO or equivalent".
- Paragraph 3.5.2.16 also should specify a lubricant type for use on pipe threads. The pipe clamps should also have this type of lubricant.
- Paragraph 3.5.2.17 should indicate that clamps used on exotic piping should use the conductive lubricant.
- Paragraph 3.5.2.23 needs clarification. What is the rationale behind using silicone prior to making the bond?
- Paragraph 3.5.3.3.2 should stipulate 2000 circular mils per running foot and feeders should be not less than #4/0 AWG.
- Paragraph 3.5.3.4 should include the ground design nomograph, multiple rod resistance chart, temperature chart, and any others affecting design.
- In the table of Paragraph 3.5.3.4.2.1, the facility and power grounds should be 1 ohm.
- Paragraph 3.5.3.4.2.2 should specify a type of instrument.
- Paragraph 3.5.3.4.3(e) should indicate that the ground rods for the facility or power ground system should conform to this spacing. The instrumentation ground must be some distance away to minimize the effects of a cathodic protection system, when used.
- Paragraph 3.5.3.4.3(f) states that exothermic welding is the only acceptable method of connection. On the basis of cost considerations, ease of welding, training and special equipment required, brazing is considered superior to the exothermic process.
- Paragraph 3.5.3.4.3(g) does not specify the method of connection to building steel.
- Paragraph 3.5.3.5.1 should stipulate that transformer banks remote (>50 feet) from the ground point may be grounded to building steel.

- Paragraph 3.5.3.5.1.1 should emphasize that the neutral shall be grounded only at one point. In addition, there should be a specific statement on what provision is to be made for opening the neutral ground connection.

- Paragraph 3.5.3.6 does not cover rack grounding. Some definite ground rules need to be added in this area.

- Paragraph 3.5.3.6.1 should include a conductive lubricant applied to the threads.

- Paragraph 3.5.3.6.8 should be expanded to cover the ACE Room equipment.

- Paragraph 3.5.3.9 indicates 10 ohms. This seems too high.

- Paragraph 3.5.3.10.2.1 needs clarification. The criteria for the use of building steel must be carefully defined. Building steel can be extremely quiet or may have hot spots. A survey is required to determine if connection to steel is feasible.

- Paragraph 3.5.3.10.2.2 mentions separate ground risers. These are probably losers by cost tradeoff. If the impedance is kept to a minimum (2000 cm/ft), the noise voltage difference between risers is probably negligible.

- Paragraph 3.5.3.10.2.3 refers to the common busbar system. This system is not widely used at KSC. It requires special care in minimizing the impedance of the bus.

- Paragraph 3.5.3.12.8 indicates a static ground resistance of 10 ohms. This seems high.

- Paragraph 3.7.2 should include instructions on inspection and test for air terminals.

- Paragraph 3.7.2.1(c) does not mention that the resistance of multiple rod arrays is a function of the spacing. A graph of this relationship should be added in place of the table.

5.2.3 Comments on KSC-STD-E-0013, Lightning Protection

The comments presented in this paragraph are related to the cited paragraphs in the subject standard.

- Paragraph 3.1 uses the term "cone of protection" before it has been introduced and defined.

- Paragraph 3.1.2 should state that the necessity for routine PMI inspection is also dictated.

- Paragraph 3.2 needs rewording -- "lightning protection systems for ... cones of protection"?

- Paragraph 3.2.1 states that buildings under 50 feet in height require no protection. The protection required depends upon the location of the buildings in relation to other structures, not upon the height of the building.

- Paragraph 3.2.3 defines "cones of protection" in a manner that is ambiguous, incorrect, and incomplete.

- Paragraph 3.3 should be entitled "Personnel Protection".

- Paragraph 3.4.7.3 should specify processes for exothermic welding of aluminum to aluminum and aluminum to copper.

- Paragraph 3.5.1.6 specifies wire gauges and areas that are excessively low when compared with AFSCF standards.

- Paragraph 3.5.12.3 is vague and requires more specific ground rules.

- Paragraph 3.6.1.1 is unclear. What is the rationale for the 30° cone of protection? NEC says 45° and MIL-B-5087B (ASG) says 60°. What is correct?

- Paragraph 3.7 somewhat contradicts Paragraph 3.5.12.3.

- Paragraph 3.8 should indicate that, ideally, the lightning counterpoise should be separate from the facility grounding counterpoise to prevent appreciable quantities of energy from being reflected into the facility and, in particular, into instrumentation facilities.

- Paragraph 4.2.1 should state that the Launch/Umbilical Towers (LUT's) should be inspected after each launch and before the LUT/vehicle is moved from the VAB.

5.2.4 Comments on DTI-E-9, Terminating and Grounding Shields for LF Instrumentation Cables

Only a general comment may be made on this specification. It does not cover the methods of grounding at the ends of cables, nor does it make any distinction between high level, low level, high impedance, low impedance, or high frequency and low frequency cables. No criteria are given for grounding, sending end, receiving end, or both ends. This specification needs further definition and rationale.

5.3 SPECIFIC SITE PROBLEMS

Specific problems involving grounding system anomalies were discovered during the Task B site Evaluation. These have been reported in detail in the Task Reports for Tasks B and C (Definition of Hazard Environment). These items together with their corrective action are summarized herein.

ANOMALY		CORRECTIVE ACTION REQUIRED
LC-34, 37, and 39		
	Lack of Compliance with Existing Philosophy	Implement compliance with consistent techniques
	Lack of Preventive Maintenance	Adoption and implementation of PMI from Task G.
	Lack of Personnel Awareness	Marking, labeling, and notification
VAB		
Tower A	- Missing Riser Section	Install riser from Rooms 3A3 to 6A3
	- E-I Compromise above Room 6A3	Locate and correct
	- E-I Compromise, Room 1A3	Remove/install surge suppressor
Tower B	- E-I Compromise, Room 1B3	Remove/install surge suppressor
	- Excessive OIS Ground Feeder	Rerun from Rooms 15B2 to 15B1A
Tower D	- E-I Compromise, Room 5D5	Connect racks to E-Ground Remove I connector.
Tower E	- Filters in Screen Room Ground	Replace filters with studs.
	- Inadequate Power Dist., Room 26E7	Add 8 neutral lines to equipment.
	- Conducted EMI Problem, Room 26E7	Add line filters to chassis.
	- E-I Compromise, Room 26E7	Remove I-Ground. Tie all equipment to E-Ground.
Tower F	- E-I Compromise, Room 1F3	Remove/install surge suppressor
Roof	- Incorrect Air Terminal Connections	Connect with metal flow process
	- Cable Rack outside Cone of Protection	Add new air terminal

LCC

Room 2R9 - E-I Compromise	Remove/add surge protector.
Room 2P10 - Chassis Ground to Anodize Upright	Add busbar for chassis grounds.
Room 2P10 - Racks not Insulated from Floor	Add plastic sheet under racks.
All Areas - Green Wire Compromise	Connect Plugmold green wire to rack.

LUT's

3AB et al - Main Ground exposed to Power Cable	Reroute and shield ground feeder.
E-I Compromises - 280-foot level	Revise cabling.
E-I Compromises - 80-foot level	Revise chassis S14-121B and 14-053.
Nebulous Grounding of ACE Units - 280-foot level	Revise ACE Room design.
No Ground Reference for ACE Room - 280-foot level	Add new 500-MCM reference cable.
No Ground Bond on Swing Arms	Provide bond across swing arms.

LC-34

Ground System in Poor Condition and Archaic	Redesign and refurbish system.
MSS Ground an unknown through Rail	Provide positive connector.

MSO

CURFCOE - Intermittent I-Ground Compromise	Insulate at floor penetration.
A-Ground - Inadequate Surge Protector	Replace with better type.
No Air Terminal on Anemometer	Add air terminal.
No Cone of Protection for Stile Stairs	Add two high air terminals on A/C duct.

Sharp bends in air terminal cables	Rerun for eight-inch minimum radius.
Loose connections to air terminals	Use metal flow process on clamps.
CIF	
No air terminals on roof	Provide air terminals for roof antennas.

5.4 SUMMARY AND CONCLUSIONS

The standards areas reported herein will be corrected during the effort on Task F, Revise and Update Criteria and Standards. The anomalies reported are recommended for correction on a routine launch-complex improvement program.

SECTION 6

REVIEW AND UPDATE CRITERIA AND STANDARDS (TASK F)

6.1 GENERAL

6.1.1 Purpose

The purpose of this task is to review and update the existing criteria and standards for bonding and grounding as delineated in KSC-STD-E-0012, dated December 29, 1969.

6.1.2 Scope

This task is based on the results of Tasks A, B, C, and D, Sections 2, 3, 4, and 5 of this volume. It proposes modification and updating of existing criteria and standards. Where appropriate, the rationale for the updating is included.

6.2 UPDATED CRITERIA AND STANDARDS

In the ensuing discussion, the paragraph numbers of KSC-STD-E-0012 are used. Additional paragraphs or subparagraphs are assigned as required. Rationale for any change is included as a lettered subparagraph. The new text is enclosed within quotation marks on the odd numbered pages, facing the original text which is on the even numbered pages.

6.2.1 Updating of Section 1 of KSC-STD-E-0012

Original

1.2 Limitations. In order to accomplish its objective, this standard necessarily delves to some extent into electrical/ electronic systems and equipment design practices. Such practices are covered only to the extent that they influence the overall bonding and grounding philosophy. Generally, additional bonding and grounding internal to the system or equipment may be required in order for the system or equipment to perform its intended function. Complete coverage of such internal bonding and grounding requirements is beyond the scope of this standard, and the determination of such requirements is the responsibility of system designers. Specific limitations in coverage of subjects mentioned, but not completely covered in this standard, are given in 1.2.1 through 1.2.4.

1.2.1 Electrical/Electronic Equipment. For individual units of electrical/electronic equipment, either facility equipment or ground support equipment (GSE), bonding and grounding requirements are specified only for the interface between the unit and its environment. Internal bonding and grounding requirements are not covered.

1.2.2 Electrical Power Systems. Bonding and Grounding practices for AC and DC power systems are specified only to the extent that such practices may effect the safety of personnel or equipment, or may be a factor in electromagnetic compatibility (EMC) control requirements. Bonding and grounding practices that may be required solely for the functional operation of power systems are not covered.

Substitute:

Paragraph 1.2 Limitations

"To accomplish its objectives, this standard necessarily delves into electrical/ electronic systems and equipment design practices. It is necessary to cover the entire spectrum of design from the individual circuit level to the total system level in order that a consistent approach to bonding and grounding may be achieved." Compromise at any hierarchical level is still compromise.

Substitute:

Paragraph 1.2.1 Electrical/Electronic Equipment

"For individual units of electrical/electronic equipment, either facility equipment or ground support equipment (GSE), bonding and grounding requirements are specified for the unit and its environment and the requirements internal to the unit. The latter are covered in general terms for use as guidelines to the equipment designer without constraining his specific approach."

Substitute:

Paragraph 1.2.2 Electrical Power Systems

"Bonding and grounding practices for ac and dc power systems are specified to cover (a.) aspects of safety to personnel and equipment, (b.) factors in electromagnetic compatibility (EMC) control requirements, and (c.) general guidelines for functional operation as they might effect overall grounding and bonding system design."

Original

1.2.4 Electromagnetic Compatibility Control Design. Unit level equipment EMC design requirements are specifically excluded from this standard. From an EMC standpoint, the bonding and grounding requirements established herein are designed to minimize the contribution of the facility environment to EMI, and to facilitate EMC techniques in systems and equipment design. Shielding of equipment or equipment enclosures, and special bonding or grounding requirements to complement shielding are not covered. Such requirements must be identified and specified by systems designers. This standard deals with EMC only insofar as bonding and grounding of facilities, and bonding and grounding of equipment to facilities, are concerned.

3.1.1 General. Some of the descriptive terminology commonly used in reference to bonding and grounding is not precisely defined, and may lead to misunderstanding of the intended meaning. The meaning of certain terms may vary, depending on the context in which they are used. In order to avoid any misunderstanding in the application of this standard, definitions and explanation of the terminology used herein are given below. It should be understood that these definitions are strictly for purposes of this standard, and that somewhat different interpretations of certain of the terms may be found in other KSC documentation and in industry literature.

3.1.2.1 Earth. That portion of the earth's crust sufficiently below the surface to act as an infinite sink or source for electric charge. Earth is considered the universal ground, or point of universal zero potential.

Substitute:

Paragraph 1.2.4 Electromagnetic Compatibility Control Design

"Unit level equipment EMC design guidelines are included herein to the extent required to ensure compatibility with system design. From an EMC standpoint, the grounding and bonding requirements established herein are more for the purpose of minimizing the contribution of the facility environment to EMI and to facilitate EMC techniques in systems and equipment design. The general guidelines for shielding of equipment and equipment enclosures and special bonding or grounding requirements to ensure effective shielding which is compatible with the facility are included."

Add:

Paragraph 2. APPLICABLE DOCUMENTS

Under "OTHER DOCUMENT", add "NFPA 78, Lightning Protection."

Substitute:

Paragraph 3.1.1 General

"In order to ensure consistent interpretation of this standard, the following definitions are presented."

Substitute:

Paragraph 3.1.2.1 Earth

"That portion of the earth's crust with which electrical contact is made consistent with the impedance parameters listed below. Earth, as such, is defined as reference zero potential level."

Original

3.1.2.2 <u>Earth Grounding Counterpoise</u>. One or more electrically interconnected driven ground rods installed for the purpose of establishing low impedance contact with Earth.

3.1.2.3 <u>Facility Ground Network</u>. This term is used to describe the electrically conductive network comprising the Earth Grounding Counterpoise and all conducting structures and grounding cables bonded thereto. In steel frame structures, the structural members bonded together and to an Earth Grounding Counterpoise form the heart of the network, with extensions provided by cable networks bonded to the structure. In non-conductive structures such as masonry buildings, and in other areas, the Facility Ground Network consists of appropriately sized conductors bonded to an Earth Grounding Counterpoise and extending to all areas containing equipment to be grounded. Functionally, the Facility Ground Network may be defined to include all metal structures that are interconnected with the Earth Grounding Counterpoise through bonded connections, to which ground connections may be made to provide conducting paths to Earth of sufficiently low impedance and adequate current-carrying capacity to meet the applicable requirements of this standard. The terms "Equipment Ground," "Structural Ground," "Earth Ground," "Facility Ground," and "Static Ground" are often used in other documentation to describe the physical and functional entity defined herein as the Facility Ground Network. The term "Facility Ground Network" does not encompass Instrumentation Ground Networks, which are defined in 3.1.2.4.

Substitute:

Paragraph 3.1.2.2 Earth Grounding Counterpoise

"One or more electrically interconnected drive ground rods installed for the purpose of establishing a reference zero potential level for a system or complex. The ensemble of the counterpoise shall have an impedance of no more than one ohm when measured by the fall-of-potential (three stake) method."

Paragraph 3.1.2.3 Facility Ground Network

"The electrically conductive network including the Earth Grounding Counterpoise and all structures and grounding cables bonded thereto, but excluding the Instrumentation Ground Network defined later. In steel frame structures, the structural members are bonded together and connected to the Earth Grounding Counterpoise to form the basic network. Extensions of this network include cable networks bonded to the structure. In buildings using non-conductive structural methods and materials, such as masonary and in outside facility areas, such as gas, propellant or oxidizer service facilities, the Facility Ground Network consists of conductors, sized according to criteria included herein, bonded to an Earth Grounding Counterpoise and extending to all areas containing equipment to be grounded.

Functionally, the Facility Ground Network is defined to include all metallic structures that are interconnected with the Earth Grounding Counterpoise through bonded connections and to which connections may be made to provide conducting paths to earth of sufficiently low impedance and adequate current carrying capacity to meet the intent of this standard. Other terms which are used to describe this network or connections to it are "Equipment Ground", "Structural Ground", "Earth Ground" and "Static Ground."

"Another item which must be noted as a part of the Facility Ground Network is the cathodic protection network. This network consists of dc power sources connected to the Facility Ground Network and to electrodes of sacrificial metals to protect those portions of the structure exposed to a hostile earth environment from galvanic erosion. In this system, the sacraficial metal acts as a cathode and is deposited on the structural members to be protected. The operation of this system may result in a potential gradient in the earth and systems connected thereto which can affect the performance of the network as a reference zero potential level. Accordingly, the design of the Facility Ground Network and its physical and electrical relation to the Instrumentation Ground Network shall include consideration of interaction with the cathodic protection network."

Original

3.1.2.4 Instrumentation Ground Network. A low impedance conductive network, electrically isolated from the ambient Facility Ground Network except for a single interconnection. Its function is to serve as a noise-free connection to Earth for a group of electromagnetically compatible equipments which may be susceptible to EMI. An Instrumentation Ground Network is the Zero Signal Reference Plane for the systems or subsystems connected thereto. The primary characteristic of an Instrumentation Ground Network is its radial nature; that is, the absence of any conductive loops within the network.

Substitute:

Paragraph 3.1.2.4 Instrumentation Ground Network

"A low impedance conductive network electrically isolated from the Facility Ground Network except for a single interconnection. Its function is to serve as a separate low impedance path to earth reference zero potential for equipment which is susceptible to the effects of EMI. This network is maintained in a radial or star configuration having no loops. In most cases, the Instrumentation and Facility Ground Networks will be one and the same."

Rationale. In the VAB and LCC, the Instrumentation Grounding Network (I-Ground) and Facility Ground Network (E-Ground) are interconnected at one point (at the base of the towers in the VAB and in Room 1R9 in the LCC). These connections were originally viewed as compromises during the early phases of the investigation. A separate counterpoise is provided for each ground system (I and E) at both VAB and LCC. In the LCC, the compromising interconnection was removed while observing the noise spectrum in the frequency domain in Firing Room 3. There was no change whatever in the observed spectrum. In Tower A of the VAB, the Instrumentation Ground Network was disconnected from the riser (and the E-Ground compromise). The impedance to earth of the counterpoise was less than 100 milliohms. There was, however, a voltage of 0.5 volts between the counterpoise and the earth near the VAB and also to the building steel. This is attributed to the cathodic protection network. A three-phase rectifier ripple of 15 mV peak-to-peak was observed between the compromise connection and the ground riser entrance point which represents the voltage drop of this current across 196 feet of #4/0 cable (see Figure 3-33). The impedance of this length of cable at 360 hertz is roughly 10 milliohms, giving the resulting current of 1.5 A peak-to-peak. Without the compromise, the noise voltage creating this current would be superimposed on every circuit it is intended to ground.

The MSO Building has a single counterpoise for all grounding systems (E, I, Static, and Signal). The LUT is still another example of a single-point ground implementation. The majority of the systems investigated use such a single-point ground very successfully.

Accordingly, in all cases, a single-point ground using a single common counterpoise should be utilized for all facilities. For the VAB, there is such a high conductivity between the structural foundation members that the base of any of the structural columns can be a low impedance connection to ground. Accordingly, each tower may have its own single point without providing significant ground loops.

Original

3.1.2.11 Power Ground. A designed connection between a power circuit conductor (neutral) and a path to Earth.

3.1.2.12 Lightning Ground. A connection between the down conductors of a lightning protection system and a Facility Ground Network.

Substitute:

Paragraph 3.1.2.11 Power Ground

"A connection between the power neutral and the Facility Ground Network. This ground shall be made at the neutral point of the distribution transformers and nowhere else. A separate power ground is required for each distribution system. It is required for personnel safety in the event of a fault and to provide a noise drain for the power system. Where a distribution system is too remote for practical connection to the Facility Ground Network, its neutral may be grounded to building structural numbers."

Substitute:

Paragraph 3.1.2.12 Lightning Ground

"A connection between the down conductors of a lightning protection system and a Lightning Ground Network."

Add:

Paragraph 3.1.2.12(a) Lightning Ground Network

"The electrically conductive network including, ideally, a counterpoise specifically for dissipating lightning energy or static discharge into the earth. On many existing structures this network and the Facility Ground Network may be one and the same."

Original

3.1.2.15 Electrical Supporting Structures. Normally non-electrified conductive structures proximate to energized electrical conductors, such that a reasonable possibility exists of accidental contact with the energized conductors. Examples are conduit and associated fittings, cable trays, electrical/electronic equipment frames and enclosures, electrical wiring cabinets, and metallic cable sheaths.

3.2.2.7 Instrumentation Grounding.

(c) It is desirable to limit the maximum dimensions of a zero signal reference plane to not more than one-twentieth of a wavelength of the highest signal frequency in the using systems. If this distance is exceeded, electromagnetic radiation from and into the using system will increase significantly.

(d) The signal amplitudes of all systems or sub-systems grounded to the same zero signal reference plane should be within an order of magnitude to minimize the possibility of interference between signals. Zero signal reference planes for equipment handling digital signals should have separate connections to the Facility Ground Network than those for equipment handling analog signals.

Substitute:

Paragraph 3.1.2.15 Electrical Supporting Structures

"Normally nonelectrified conductive items which carry or are adjacent to energized electrical conductors so that a reasonable possibility exists of accidental contact between these items and the conductors. Examples of these items are:

Conduit and fittings

Cable trays and ducts

Electrical/electronic equipment frames and enclosures

Electrical wiring cabinets

Metallic cable sheaths"

Delete:

Paragraph 3.2.2.7(c) Instrumentation Grounding

Rationale. The paragraph, as written, does not describe a practical and realizable condition. The wavelength of the highest signal frequency is in the vicinity of 50 millimeters. One twentieth of this is 2-1/2 millimeters.

Delete:

Paragraph 3.2.2.7(c

Rationale. The idea of maintaining within an order of magnitude the signal amplitudes of the systems connected to a zero signal reference plane is inconsistent with the philosophy of a grounding system. A grounding system has, by definition, a low enough impedance to act as a drain for noise of any amplitude with little interaction with other systems. With regard to providing separate zero signal reference planes for digital and analog equipments, if the several rules regarding conductor sizing and treatment contained in the following paragraphs are followed, the impedance at any plane will be low enough to preclude any interaction between systems. However, for high frequency analog systems (above 2 MHz) it is more expedient to use the E-Ground (building steel) for grounding since the impedance of the zero signal reference plane may be very high in the range of 2 MHz and above (e.g., 1800 ohms at 10 MHz). The steel with a resistivity 10 times that of copper, will have a deeper skin depth (approximately 3 times that of copper), about 30 times greater perimeter (for #4/0 cable versus a 12-inch I-beam, for example) and, consequently, 90 times greater conducting area at 10 MHz. Other factors, such as rms surface roughness and concentration of current at the edges will increase the resistance by a factor of 4. Accordingly, a 12 inch I-beam will have an ac resistance at 10 MHz which is 0.44 that of the #4/0 copper cable. In addition, the steel has the advantage of many parallel paths -- the building framework.

3.4.2.1 Electrical Power Systems. AC power distribution systems shall be grounded as specified in 3.5.

3.4.3.1 Zone 1. In areas classified as Zone 1, all exposed metal objects exceeding 48 inches in any dimension shall be bonded to ground. Unexposed metals, such as reinforcing steel completely encased in concrete, objects completely buried, or objects completely contained in hazardproofed locations, do not require bonding or grounding as a Zone 1 requirement.

3.4.3.2 Zone 2. Within areas classified as Zone 2, all metal objects exceeding six inches in any dimension which are in physical contact with other metal objects exceeding six inches in any dimension shall be bonded together at the contact junction. If the junction exceeds six inches in any dimension, bonds shall be established across the junction at six inch intervals.

Substitute:

Paragraph 3.4.2.1 Electrical Power Systems

"AC power distribution systems shall be grounded at one point only as specified in Paragraph 3.5."

Add:

Paragraph 3.4.3.1 Zone 1

(d) Rationale. During a thunderstorm, electric field intensities on the surface of the earth often reach levels in excess of 100 V/cm. This zone is defined as one in which an explosive atmosphere may be present and any arcing must be avoided. With a field intensity of 100 V/cm, arcing can occur between pieces of metal, one of which is grounded and the other having a longest dimension of 48 inches and separated by 0.15 inch. Sufficient energy (0.02 millijoule) can be stored to ignite an optimum mixture of hydrogen, between two 48-inch wires separated by this distance. The relation between the dimension and separation from other metal for arcing condition with a field intensity of 100 V/cm is shown in Figure 6-1. In every case, more than enough energy is stored and released in the arc to ignite a 6-percent air-hydrogen mixture (by volume).

Add:

Paragraph 3.4.3.2 Zone 2

(e) Rationale. Zone 2 is defined as one containing antennas associated with sensitive receivers. There is always a possibility of the generation of higher-order products which lie within the passband of these receivers if two pieces of metal with a nonlinear junction between them are irradiated at the proper frequency. As stated in the description on Task C, Hazard Environment, a sizable level of power density is required to achieve higher-product radiation of the level required to interfere with the operation of the receivers -- even assuming perfect diodes. In addition, frequency discipline in the selection of operating frequencies has precluded the generation of an interfering product. In the interest of preventing the generation of any such products, the bonding dimension requirement of six inches was established. Six inches is a quarter wavelength for a frequency of 450 MHz. The most significant product which could be generated by a nonlinear junction at this frequency is 1350 MHz. This is below the operating frequency of any of the receivers used on the Saturn V/Apollo vehicle. The fifth harmonic of the fundamental is within the passband of the USB receivers but would be under the receiver threshold.

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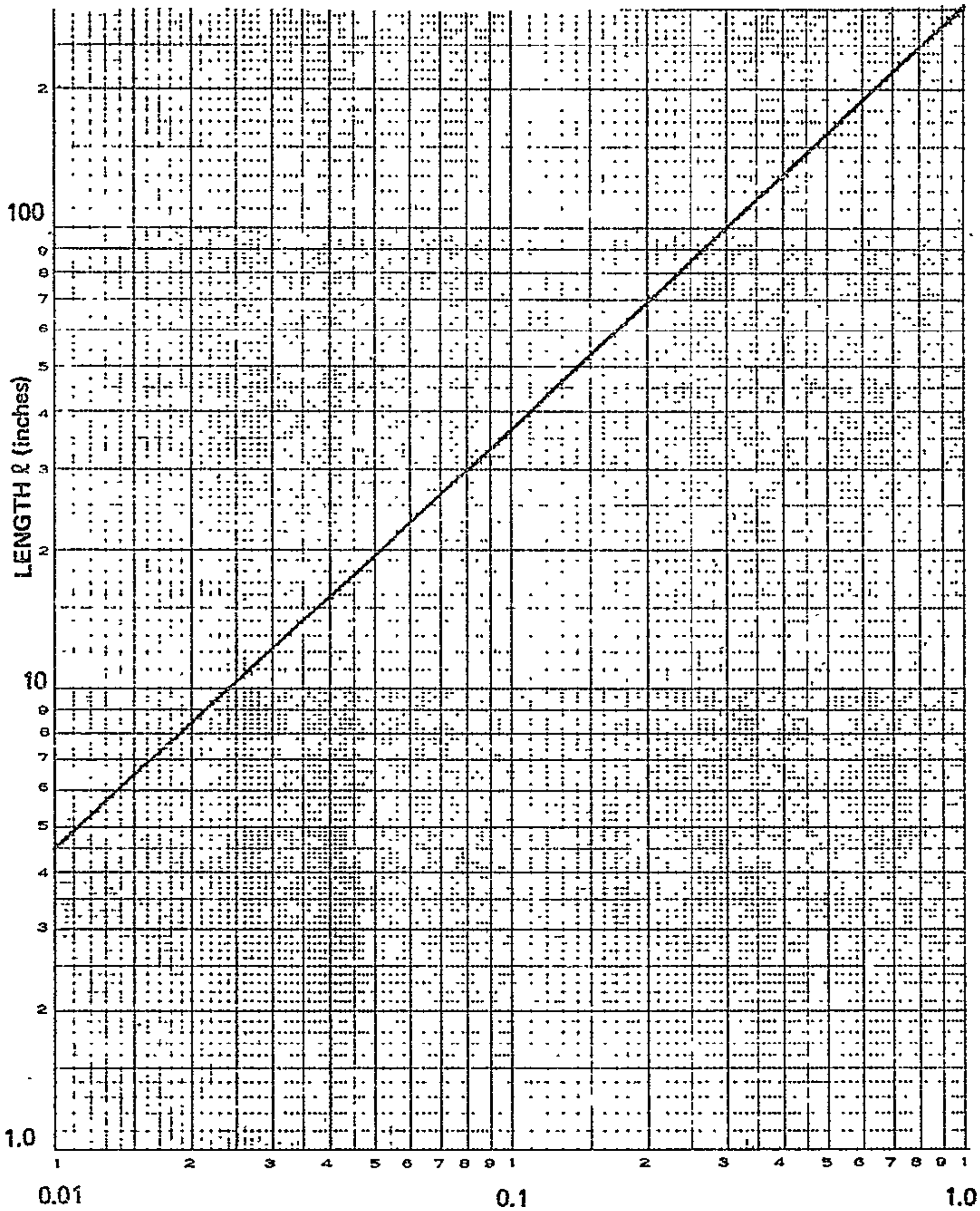

LONGEST DIMENSION vs SEPARATION FOR ARCING
(ELECTRIC FIELD INTENSITY – 100 V/cm)

Figure 6-1 Arcing Criteria in High E-Field

3.5.2.1.4 Clamping. In external locations, clamping shall be used only where a disconnect type of connection is required. The connecting device may utilize either spring loaded jaws or threaded fasteners. The device shall be so constructed that positive contact pressure is maintained at all times. This method includes the use of machine bolts with tooth type or spring type lock washers.

3.5.2.1.6 High-Strength Structural Bolting. Joints made with high strength structural bolts, and clean unpainted faying surfaces shall be considered as sufficiently bonded to meet the electrical requirements of this standard. The term "clean" as used herein shall mean that faying surfaces on new steel shall have been blasted to bare metal. Where this condition does not exist, this standard would consider sufficient a jumper in the form of a No. 4 AWG bare copper wire exothermally welded at each end to the surfaces involved spanning the connection; or a bond weld, defined as a 1/4-inch or larger fillet weld, with a 2-inch minimum length across the connection. Wire jumpers shall be used across joints employing miscellaneous machine bolts such as those used in stairway construction.

Substitute:

Paragraph 3.5.2.1.4 Clamping

"In external locations, clamping shall be used for bonding or grounding only on a temporary item, such as a barrel or high pressure gas tank, where a quick-disconnect type of connection is required. The connecting device may utilize either spring-loaded jaws, threaded fasteners, or machine bolts with tooth or spring-type lock washers and shall be so constructed that a positive pressure is maintained at all times. The surface to which it is attached shall be cleaned with 200-grit carborundum paper to remove all paint or oxide. After attachment, a silicon grease shall be applied to the area of the connection to preclude oxidation."

Substitute:

Paragraph 3.5.2.1.6 High Strength Structural Bolting

"Joints made with high strength structural bolts and clean, unpainted faying surface shall be considered as sufficiently bonded to meet the electrical requirements of this standard, providing the minimum torquing requirements listed below are met."

Add:

Table 3-1

Minimum Torquing Requirement

Bolt Size	Threads/Inch	Min. Torque (in-lbs)	Tension (lbs)
#8	32	18	625
	36	20	685
#10	24	23	705
	32	32	940
1/4"	20	80	1840
	28	100	2200
5/16"	18	140	2540
	20	150	2620
3/8"	16	250	3740
	24	275	3950
7/16"	14	400	5110
	20	425	5120
1/2"	13	550	6110
	20	575	6140
5/8"	11	920	7350
3/4"	10	1400	9300
7/8"	9	1950	11100
1"	8	2580	12900

"The term "clean" as used herein shall mean that faying surfaces on new steel shall have been sandblasted to bare metal. Where it is impossible or impractical to achieve a clean faying surface, a #2/0 AWG bare copper wire shall be exothermally welded at each end to the surfaces to be bonded, thus spanning the joint. Another method which may be used is the provision of a bonding fillet weld between the two surfaces. This fillet shall be at least 1/4-inch and shall span at least 2-inches of the joint."

3.5.2.3 Cleaning of Mating Surfaces. All mating surfaces which comprise the bond shall be thoroughly cleaned before joining to remove oxides and other resistance films from the mating surfaces. All organic films; such as grease, oil, corrosion products, rust, zinc chromate, paint lacquer, and inorganic finishes; such as anodize, alodine, corrosion preventive compounds and moisture shall be removed before bonding. Paint and other organic finishes shall be removed from the metal base with an air operated orbital sander, or equivalent, using 400 grit abrasive paper. Removal of inorganic finishes shall be accomplished by using abrasive paper or cloth backed abrasive 320 grit or a rubber abrasive bonding brush. Gentle and uniform pressure shall be used to insure a smooth, uniform surface without "point contacts." Excessive metal shall not be removed from the surface. Bare metal shall then be cleaned with a solvent-moistened cheese cloth. Grease, oil, dirt, corrosive preventatives, and other contaminants shall also be removed using this same method.

3.5.2.3.2 When it becomes necessary to remove a protective coating from metallic surfaces to meet bonding requirements, the affected areas shall be refinished within 48 hours. If additional time is needed, a corrosion preventative coating shall be applied until the bond is made or the area can be refinished to match the original finish.

3.5.2.6 Bonding Straps and Jumpers. Bonding straps and jumpers (Figure 3-2) shall be solid metal unless otherwise specified, and shall have a cross sectional area not less than that of a No. 6 AWG copper wire. Bonding jumpers shall conform to MS-25083.

Change:

Paragraph 3.5.2.3 Cleaning of Mating Surfaces

Change last two sentences to read, "Bare metal shall then be cleaned with trichlorethylene. Grease, oil, dirt, corrosion preventatives, and other contaminates shall be removed in this manner.

CAUTION: Trichlorethylene and related solvents are a cumulative poison which may be absorbed by the lungs or the skin. Accordingly, all precaution should be taken to prevent contact with the skin and to avoid breathing the vapors."

Substitute:

Paragraph 3.5.2.3.2

"When it becomes necessary to remove a protective coating from metallic surfaces to install a bonding device, the bond shall be attached within 30 minutes after cleaning. The surfaces shall be refinished within two hours to prevent oxidation. If additional time is required, a corrosion preventative shall be applied until the area can be refinished."

Substitute:

Paragraph 3.5.2.6 Bonding Straps and Jumpers

"Bonding straps and jumpers shall be of solid copper unless otherwise specified and shall have a cross-sectional area of 2000 cmil/ft but no less than that of #6 AWG wire (0.02062 in^2 or 26,250 cmils). Bonding straps and jumpers for shock mounted devices shall not affect the dynamic characteristics of the device as mounted and shall be made of flat tinned copper woven wire braid. Acceptable sizes and their circular mil (cmil) equivalent are as follows:

Approximate Width (in.)	Area (cmil)
1	26,000
1-1/2	52,500
2	80,000

Vibration of the strap or jumper by the shock mounted device shall not change its electrical characteristics. Bonding jumpers shall conform to MS-25083. Where bonding jumpers and straps are bolted, the tightening torque shall conform to Table 3-1."

<u>Original</u>

3.5.2.7 <u>Joints</u>. Pivot, hinged, and swivel joints shall have a braided jumper connection across the joint that will require minimum flexing while in use. Bonds shall be brazed, or welded in external locations. Clamping methods may be used for bonds in internal locations if continuous pressure follow-up is provided in the design.

3.5.2.13 <u>Bonding of Cable Trays</u>. Cable trays sections, whether in single runs or in system arrangement, shall be bonded together as shown in Figure 3-4. Specific bonding concern is directed to the location of cable trays in the outdoors, where an aluminum tray may be grounded through the bond of a copper conductor. The dissimilar metal bond of this situation requires that the potential corrosion problem be avoided using a bimetallic connector, treated with a conductive, corrosion preventive lubricant. Cable

3.5.2.16 <u>Pipe-General</u>. Pipe shall be bonded to ground at intervals of not more than 100 feet. For internal locations bonding may be by clamping methods if continuous pressure follow-up is provided with serrated or spring washers. External locations shall have brazed or welded bonds - except that stainless steel clamps may be used to bond stainless steel pipe to ground if the restrictions of dissimilar metals as presented in this standard are considered. Threaded joints which have a tapered thread are acceptable if drawn up tightly with a corrosion inhibiting conducting sealant during assembly for internal or external locations to assure an adequate bond across the joint. Flange areas shall be clean and bright where in contact with the bolt heads and washers. Tubing with seated fittings are considered adequately bonded through the sweated joints.

Change:

Paragraph 3.5.2.7 Joints

"external" and "internal" to read "outdoor" and "indoor", respectively."

Add:

Paragraph 3.5.2.13 Bonding of Cable Trays

At the end of the third sentence, beginning "The dissimilar metal bond ....." add "(Eccoshield Type SO Conductive Lubricant or equivalent)".

Change:

Paragraph 3.5.3.16 Pipe - General

"Change the fourth sentence, beginning, "Threaded joints ....." to read, "Threaded joints which have a tapered thread are acceptable if drawn up tightly with a corrosion-inhibiting conductive sealant (Eccoshield Conductive Pipe Compound or equivalent) to ensure an adequate, lasting bond across the joint."

3.5.2.17 Exotic Piping. Bi-metallic and vacuum jacketed piping shall be bonded by clamps or by previously attached grounding lugs and pigtails of compatible materials.

3.5.3.3.1 Metal Frame Structures. In metal frame structures the structural members shall constitute the core of the facility ground network and shall be grounded to an earth grounding counterpoise in accordance with 3.5.3.4.3. Extensions of the facility ground network to areas where bonded structural members are not accessible shall be accomplished with copper conductors bonded to major structural members. Conductor sizes shall be such that the total resistance of any copper conductor extension, including connections, does not exceed five (5) milliohms, but shall not be less than No. 2/0 AWG. Equipment ground connections shall be made only to bonded structural members larger than two (2) square inches in cross-sectional area, or to the copper conductor extensions. Ground connections shall not be made to miscellaneous metal structures such as partitions, railings, gratings, etc., even if these structures are grounded.

3.5.3.3.2 Non-Metal Structures and Exterior Areas. In nonmetallic structures and exterior areas where grounding is required, an earth grounding counterpoise in accordance with the applicable requirements of 3.5.3.4.3 shall be provided, and copper conductors extended from the counterpoise to all areas where grounding is required. The sizes of the copper conductors shall be such that the resistance between any point in the facility ground network and the earth grounding counterpoise does not exceed ten (10) milliohms, but shall not be less than No. 2/0 AWG. In Zone 4 areas, electrical conduit systems may be utilized as a part of the facility ground network and equipment ground connections made thereto, provided that the conduit systems are bonded and grounded as specified in 3.5.3.6.1.

Substitute:

Paragraph 3.5.2.17 Exotic Piping

"Bi-metallic and vacuum jacketed piping shall be bonded by clamps or by previously attached grounding lugs and pigtails of compatible materials. Eccoshield Type SO conductive lubricant or equivalent shall be used between the pipe clamps and the pipe."

Change:

Paragraph 3.5.3.3.1 Metal Frame Structures

Change the third sentence, beginning, "Conductor sizes ....", to read: "Conductor sizes shall be selected on the basis of providing 2000 cmil of cross-sectional area for each running foot of the extension but shall not be less than #4/0 AWG."

Change:

Paragraph 3.5.3.3.2 Non-Metal Structures and Exterior Areas

Change the second sentence beginning, "The sizes of copper ....", to read: "Conductor sizes shall be selected on the basis of providing 2000 cmil of cross-sectional area for each running foot of the extension from the earth grounding counterpoise but shall not be less than #4/0 AWG."

3.5.3.4.3 Counterpoise Design Requirements.

(a) The rod-to-earth resistance of individual ground rods shall be in accordance with the requirements of 3.5.3.4.2.1 applicable to the most stringent grounding requirement for which the counterpoise will be used.

Substitute:

Paragraph 3.5.3.4.3(a), Change

Change to read: "The counterpoise-to-earth resistance shall be in accordance with the requirements of Paragraph 3.5.3.4.2.1 which are applicable to the most stringent grounding requirement for which the counterpoise will be used. A design nomograph for an individual ground rod is shown in Figure 6-2. An early part of the counterpoise design will be the measurement of the resistivity of the earth in the vicinity where the counterpoise will be installed. This will be done using the four-stake method with a Model 293 Vibroground or equivalent. The resistivity at the depth of 4, 8, 16, and 32 feet shall be determined by varying the spacing between the test stakes accordingly. The 32-foot measurement represents an average resistivity to that depth and shall be used, together with the diameter (3/4-in) and required resistance, to determine the length of rod required. Some cautions must be pointed out in the use of this nomograph. These are:

(1) If the solution indicates a rod length of 16 feet or less, the length shall be redetermined using the measured resistivity for that depth. Likewise, an indicated length of 8 feet or less or 4 feet or less dictates that the corresponding resistivity should be used.

(2) If the determined rod length is off-scale because of ground resistivity, a multiple-rod counterpoise shall be considered. Select an arbitrary rod length and determine the resistance for that length. Then, using the multiple rod conductive ratio chart of Figure 3-2, determine the number of rods of that resistance required to achieve the desired net resistance.

The equations described by the nomograph and the multiple rod chart are as follows

(3) Single-Rod Resistance

$$R = \frac{\rho}{2\pi L} \left(\log_e \frac{4L}{A} - 1\right)$$

R = earth ground resistance, ohms

L = rod length, cm

A = radius of rod, cm

ρ = resistivity, ohm-cm

(4) Multiple-rod resistance

$$R_N = \frac{1}{N} \frac{\rho}{2\pi L} \left[\log_e \frac{4L}{A} - 1 + \frac{2L}{S} \log_e \quad 0.657N \right].$$

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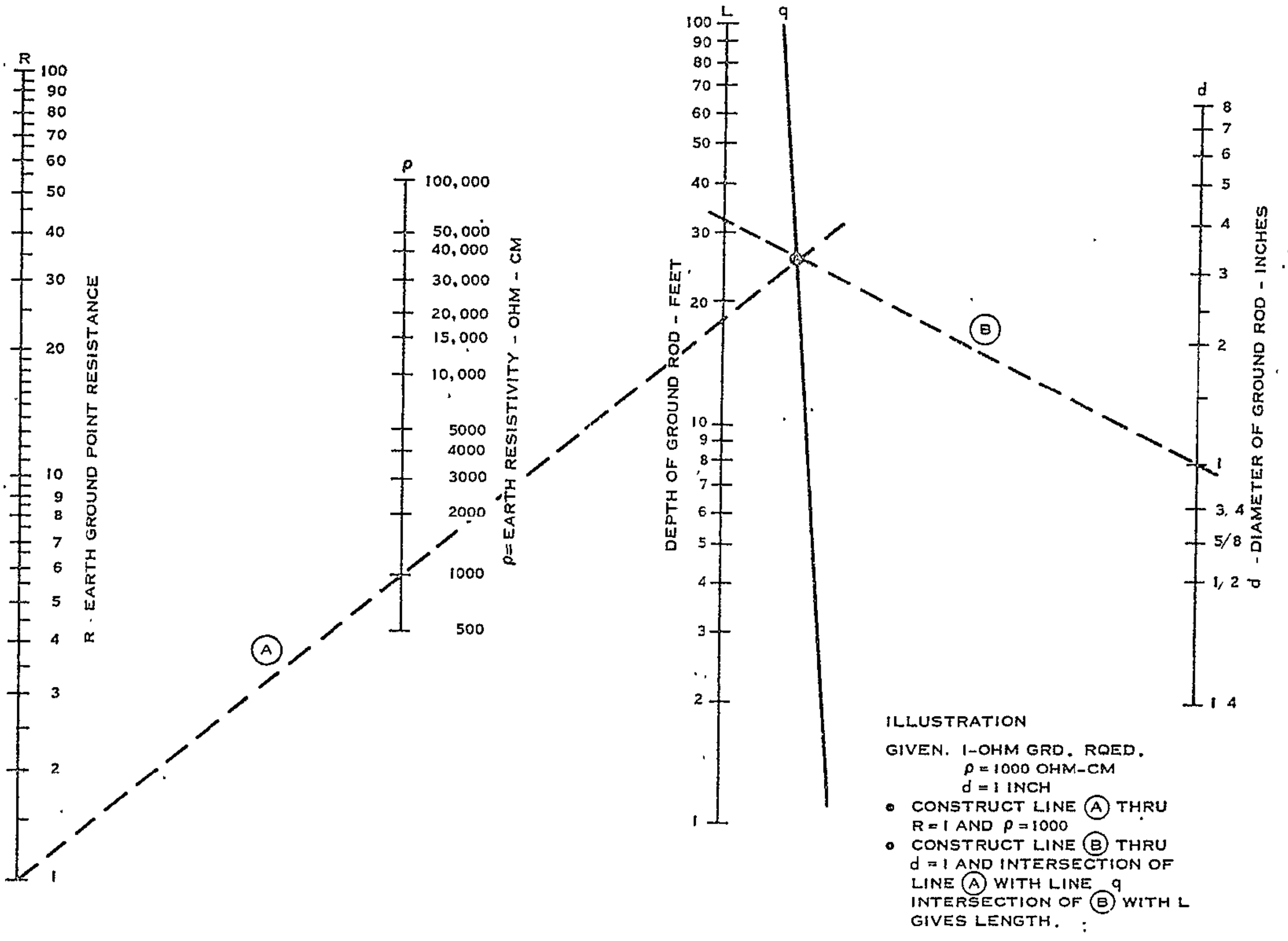

Figure 6-2 Nomograph for Earth Ground Point Design

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where

N = number of rods

S = spacing between rods, cm

All other parameters are defined in A.

(5) Interconnecting path. Where interconnecting paths, as covered in Paragraph b, are required and copper cable is used, the ground resistance of the cable is in parallel with the resistance of the rod ensemble. This resistance can be calculated as follows:

$$R = \frac{\rho}{4\pi L_h}\left(\log_e \frac{4L_h}{A} + \log_e \frac{4L_h}{S} - 2 + \frac{S}{2L_h} - \frac{S^2}{16L_h^2} + \frac{S^2}{512L_h^4} \cdots\cdots\right)$$

where

R_h = ground resistance of horizontal interconnecting path

L_h = one-half the length of the path, cm

A = radius of cable

S = twice the depth of burial

The total resistance of the total ensemble of multiple equally spaced rods and interconnecting paths is

$$R_t = \frac{MR_hR_n}{MR_h + R_n}$$

where

R_t = total ground resistance of ensemble.

M = number of interconnecting paths

R_h and R_n as above

If the connection from the counterpoise ensemble to the ground network is bare cable, its resistance must be calculated as above and included in the ensemble as

$$R_t' = \frac{MR_hR_cR_n}{R_cMR_h + MR_hR_n + R_nR_c}$$

where

R_c = ground resistance of connecting cable

R_t = total ground resistance of ensemble with bare copper connecting cable

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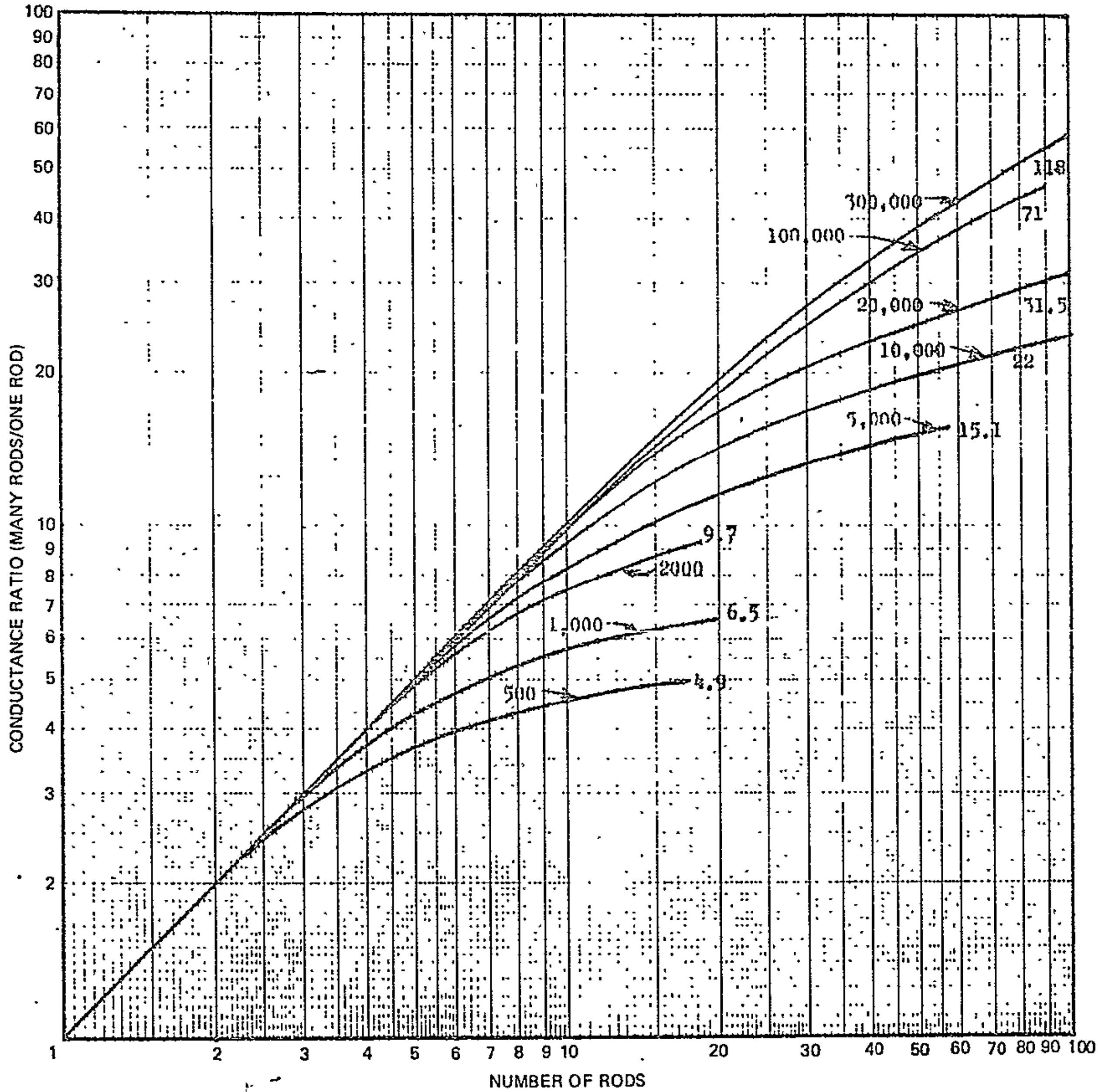

NUMBERS ON CURVES ARE AREAS OVER WHICH RODS ARE DISTRIBUTED.

NUMBERS AT ENDS OF CURVES ARE RATIOS FOR INFINITE NUMBER OF RODS OVER AREA

Figure 6-3 Conductance Ratio of Many Rods vs One Rod in a Given Area

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Original

3.5.3.4.3 Counterpoise Design Requirements.

(f) Wire connections to ground rods, and riser connections to counterpoise wires, shall be made by exothermic welding only. The wires, or wire and rod, shall be placed in parallel contact and continuously welded for a distance of at least two (2) inches.

(g) When counterpoises are provided for steel frame structures, each vertical column to be grounded shall be separately connected to the counterpoise by the most direct route with No. 4/0 AWG, or larger, copper conductors. Additional risers from the counterpoise to above grade level may be required for special grounding purposes.

(h) When counterpoises are provided for other than steel frame structures in Zone 1, 2, and 3 areas, riser conductors from the counterpoise to above grade level shall be provided at intervals not exceeding 50 feet. The risers shall be routed to the nearest interior (for enclosed structures) or protected area. Risers shall be No. 4/0 AWG, or larger, copper conductors, and shall be routed along a protected route.

3.5.3.5.1 AC Power Distribution Systems. Sixty Hertz AC power distribution systems, for both industrial and instrumentation power, shall have the neutral conductor grounded to the facility ground network at the immediate power source (transformer secondary or generator). In all facilities which contain any Zone 1, 2, or 3 areas, all distribution circuitry downstream of this ground connection (Power Ground) shall be isolated so that no current normally flows through the ground conductor or through the facility ground network. Zone 4 areas shall meet NEC requirements on neutral grounding.

Substitute:

Paragraph 3.5.3.4.3(f)

"Wire connections to ground rods and riser connections to counterpoise wires shall be made by brazing or an exothermic welding process. The wires or wire and rod shall be placed in parallel and in contact and continuously brazed or welded for a distance of at least two inches."

Add:

Paragraph 3.5.3.4.3(g)

Add "Conductors shall be attached to the column by brazing or exothermic welding in the manner specified in (f) above."

Change:

Paragraph 3.5.3.4.3(h)

Change the last sentence to read: "Riser conductors shall have a cross-sectional area of 2000 cmil for each running foot of riser length, but shall not be less than #4/0 AWG. The risers shall be routed by a route which avoids by at least 3 feet any other conductors or cables. Where this requirement cannot be met or in areas of high ambient noise (E and/or H field), the riser shall be run in aluminum or ferrous conduit."

Change:

Paragraph 3.5.3.5.1 AC Power Distribution Systems

Change the first sentence to read: "Sixty-hertz AC power distribution systems for both industrial and instrumentation power shall have the neutral conductor grounded to the Facility Ground Network only at the immediate power source (transformer secondary or generator)."

Original

3.5.3.5.1.1 Power Sources. Transformers for single phase or three phase supply at 600 volts nominal, or less, shall have their secondaries grounded as shown in Figure 3-6. Generator neutral conductors shall be grounded in a similar manner. When generators are operated in parallel, the neutrals shall be bussed together and grounded at a single point. The ground connection shall be made to the nearest accessible point on the facility ground network. The grounding conductor size shall be such that the resistance of the path between neutral conductor and the facility ground network, including connections, does not exceed two milliohms, but in no case shall be less than the size specified by the National Electrical Code. For power sources supplying power to Zone 1, 2, or 3 areas, provisions shall be made for opening the neutral ground connection for neutral isolation testing as specified in 3.7.

3.5.3.6.1 Conduit Systems.

(b) All joints between conduit sections or between sections and fittings or boxes shall be bonded. Conduit terminations in terminal equipment junction boxes shall be bonded. Threaded connections are considered adequately bonded. Conduit couplings, terminations in thinwall boxes, and fittings made with gouging lock nuts or grounding bushings are adequately bonded. All other joints shall have bonded jumpers installed across the joints.

Change:

Paragraph 3.5.3.5.1.1 Power Sources

Change the sentence beginning, "The grounding conductor size...." to read: "The grounding conductor size shall be selected to provide a cross-sectional area of 5000 cmil for each running foot of the neutral grounding conductor, but in no case shall be less than the size specified by the National Electric Code. Power sources supplying any zone classification shall include provision for opening the neutral ground connection for neutral isolation testing as specified in Paragraph 3.7.1(a). This device shall have a cross section at least equal to that of the neutral ground cable and shall be capable of being sealed for integrity control."

Change:

Paragraph 3.5.3.6.1(b)

Change the sentence beginning "Threaded connections ....", to read: "Threaded connections are considered to be adequately bonded when the threads are treated with a conductive lubricant (Eccoshield Type SO or equivalent) and the threads are firmly tightened."

Add:

Paragraph 3.5.3.6.9 Electronic Equipment Enclosures

"Electronic equipment enclosures may be associated with either the facility ground network or the instrumentation ground network, depending upon the nature and sensitivity of the equipment contained therein. When an enclosure is associated with the instrumentation ground network, it shall be isolated from the facility ground network by placing an insulating sheet of phenolic or similar material between its base and the floor. The internal enclosure grounding shall be arranged as follows:

(a) A ground lug shall be welded to the base of the enclosure for connection to the appropriate ground network.

(b) A 1/4-inch by 1-inch copper busbar shall be attached to the left-hand vertical upright (as viewed from the rear) for providing chassis grounds. This busbar shall be connected to the enclosure ground by using 1/0 cable.

(c) Where separate signal (E-2) grounds are included as a design feature of equipment in the enclosure, a similar busbar shall be provided on the right-hand upright and shall be insulated from the cabinet. This busbar shall be connected to the enclosure ground lug when the enclosure is

Original

3.5.3.10.2.1 Structural Steel as System Ground Point. This grounding scheme utilizes the structural steel in the structure as a low-impedance extension of the earth ground. Individual instrumentation and communication system reference planes are single-point grounded to the building steel at the nearest, most convenient point. The electrical conductivity of steel is approximately 12 to 14 percent that of standard annealed copper with 100 percent conductivity. Figure 3-8 is a schematic representation of this scheme.

3.5.3.10.2.2 Separate Ground Risers. This scheme requires that each individual instrumentation and communication system reference plane be connected to earth ground at one common point through the use of separate insulated grounding conductors. The major disadvantage to this scheme is the difficulty in maintaining equipotential voltages between systems. Figure 3-9 is an illustration of this scheme.

3.5.3.10.2.3 Use of Common Bus as Ground Point for Systems. This scheme calls for an insulated ground bus to be routed radially through the structure to form a grounding "tree," the main trunk of which is a large, grounded copper bus. This method has two major faults. First, it requires that all connected reference planes be compatible, i.e., like signals. Second, it generates current flow between systems due to finite impedances and differences of potentials. Figure 3-10 illustrates this scheme.

3.7.2.1 Testing Procedures.

(c) The maximum allowable resistance for multiple rod counterpoises shall be as follows:

NO. OF RODS	MAXIMUM RESISTANCE
2 to 4	$2\ R_1/N$
5 to 8	$3\ R_1/N$
9 or more	$4\ R_1/N$

Where R_1 = Maximum resistance of individual rods

N = Number of rods in counterpoise

associated with the instrumentation ground network or, in the case where the enclosure is connected to the facility ground network, this busbar shall be connected to the nearest point on the instrumentation ground network."

Add:

Paragraph 3.5.3.10.2.1 Structural Steel as System Ground Point

"This ground scheme is particularly suited to the grounding of high frequency devices operating at 2 MHz or higher. While the resistivity of steel is approximately ten times that of copper, the skin depth is $\sqrt{10}$ or 3.17 times greater than that of copper, thereby affording greater area for high frequency conduction. This advantage is offset somewhat by the rms surface roughness, which results in a longer path for high frequency currents and the tendency of the current to concentrate at the edges of the beam. Before using building steel at a specific location, noise at that location in reference to the counterpoise connection should be examined in both the time and frequency domains to ascertain that there is no excessive machine noise or standing noise from an external source which would tend to degrade the performance of the equipment to be grounded."

Change:

Paragraph 3.5.3.10.2.2 Separate Ground Risers

Change the last sentence to read: "The major disadvantage to this scheme is the cost of implementation versus the advantage gained. There is no appreciable problem of developing serious potential differences between such risers if the 2000 cmil cross section per running foot of riser criterion is followed in the grounding system design."

Add:

Paragraph 3.5.3.10.2.3 Use of Common Bus as Ground Point for Systems

"This type of system is particularly applicable to a system having wide distribution and requiring a common low impedance ground." An example is the ACE system in the MSO and LC-39 LCC which uses large copper pipe busbars for Signal and Static Ground.

Change:

Paragraph 3.7.2.1(c)

Change to read, "The maximum allowable resistance for multiple rod counterpoises shall be determined through the charts and procedures of Paragraph 3.5.3.4.3(a)."

SECTION 7

SUMMARY AND CONCLUSIONS

7.1 SUMMARY

The material presented in this volume represents an analysis of the bonding and gounding requirements and implementation at the Kennedy Space Center. It gives consideration to what is being done elsewhere, to the special problems encountered at KSC, and to the techniques recommended above and beyond the present standards to solve these problems. The solutions are presented in Volume I, "Criteria for Bonding and Grounding at Kennedy Space Center", and Volume III, "Preventive Maintenance Instructions for Bonding and Grounding at Kennedy Space Center".

7.2 CONCLUSIONS

The conclusions which may be drawn are summarized as follows:

a. In general, the existing grounding philosophy, both as written and as implemented, is a good one and is consistent with the philosophy applied in similar types of installations other than KSC.

b. A problem exists where, through lack of sufficient detail in existing criteria, individual contractors have introduced practices which resul in a compromise of an otherwise valid philosophy.

c. A problem exists where personnel are uninformed, where grounding system components are unmarked, and the grounding system is inadvertently compromised.

d. A problem exists as a result of the lack of good maintenance practices on a timely and periodic basis and, accordingly, grounding system anomalies remain undetected and uncorrected.

e. The three grounding schemes described in Paragraph 3. 5. 3. 10. 2 of KSC-STD-E-0012 are implemented and all appear to have a place in the overall system. The criteria for their use are as follows:

- Structural steel should be used as a ground point for high frequency devices operating above 2 MHz and where susceptibility to low frequency noise is not a problem. At 2 MHz and above, the impedance of the copper risers of any practical size becomes significantly higher than that of the structural steel. As a result, the question arises as to the effectiveness of conventional copper grounding systems as a noise sink.

- The use of separate ground risers to each individual system is highly desirable in systems operating below 2 MHz, providing the impedance of the risers is low enough (less than one ohm at the highest fundamental frequency involved).

- From the cost-effectiveness standpoint, the use of separate risers is not always feasible. In these cases a common bus system represents the best compromise. Here again the conductors must be sized to provide a sufficiently low impedance to be effective as a noise drain safety ground and to minimize common mode voltages.

f. While the production of higher-order frequencies, when a nonlinear junction is irradiated with an RF signal, is indeed a real phenomenon, it does not present a significant problem at KSC because of the judicious choice of operating frequencies. The power levels at KSC are below the critical values required to develop interference products of significant power.

g. Safety measures, particularly the compulsory training of personnel at KSC, minimize the probability of injury or damage resulting from any of the defined hazards.

h. A principal source of conducted interference, in frequencies from 200 to 300 kHz, was found to be the solid state (SCR) regulated power supplies. This noise is conducted to other systems via ac power leads and the grounding system.

SECTION 8

RECOMMENDATIONS

8.1 GENERAL

This section contains recommendations for efforts required to remedy reported anomalies in the bonding and grounding implementation so that it will be compliant with the criteria delineated in Volume I.

8.2 IMPLEMENTATION OF PMI'S

A major contribution to the overall general condition and effectiveness of the bonding and grounding at KSC is the implementation of the Preventive Maintenance Instructions contained in Volume III, at the intervals specified. In this implementation, a checklist should be developed which lists the location of each item to be routined. This list should contain, typically, the location of all E-plates and I-plates, ground points, ground rods for resistance measurements, etc. Some items are so numerous that listing them by class is sufficient. For example, bonding on the fire alarm boxes on a LUT can be listed as a class since there is a box on each level placed at the same relative location near the stairwell.

8.3 IMPLEMENTATION OF MARKING, LABELING, AND PROTECTION

Many compromises of bonding and grounding noted during the on-site evaluation effort were the results of the lack of information or warning of the nature of the grounds and their vulnerability to compromise. To offset this factor, it is recommended that the items delineated in Paragraph 3.5.3.12.9 of Volume I of this report regarding marking, labeling, and protection be implemented. This, coupled with a general information memorandum to employes who work in or pass through areas where bonding and grounding details are present, will do much to prevent inadvertent compromise or damage.

8.4 SCR POWER SUPPLY NOISE REDUCTION

The greater portion of the noise in the 200- to 300-kHz range which appears on the grounding and power systems was found to originate in the SCR regulated power supplies used to power semiconductor circuitry. This noise appears as a highly damped oscillation following the SCR turn-on spike. (Figure 3-50, Section 3.) Philco-Ford has previously encountered similar noise in other installations. This noise probably occurs as a result of resonance of the filter capacitors. It apparently does not appear in the dc load — only on the ground and power lines. Noise on the ground and power lines is reflected back into other systems and tends to degrade their performance. A study effort should be initiated to determine the origin of this noise and the most cost-effective method for its reduction. In this cost-effective consideration, the method of correction selected should be chosen with regard to reduction of the turn-on spike as well as reduction of the 200- to 300-kHz noise.

8.5 CABINET/CHASSIS/POWER GROUNDING ANOMALIES

One of the most widespread anomalies found in the on-site evaluation is the manner in which the "green-wire" or power ground is treated at the various hierarchies of the equipment installation. In its present treatment, at least in many instances observed, the green wire is connected in such a manner that it forms a compromise between the E- or I-Ground and the power ground. In this compromise, the green wire is extended from the power distribution panel to the plugmold receptacles in the equipment enclosures and, via the chassis power cord, to the chassis. The chassis is already connected to E-Ground or I-Ground through the enclosure or enclosure ground bus. It is estimated that more than 1,000 enclosures (racks and consoles) are involved. It is recommended that this compromise be corrected by changing the plugmold receptacle grounds to connect to the associated enclosures ground point rather than the green wire from the distribution panel. A test case should be run on a group of isolated racks which are so connected and the improvement (reduction of noise on the chassis) be determined. If a reduction of 2 dB or more is realized, then it will be cost effective to perform this modification wherever the anomaly appears at KSC.

8.6 NEW LC-34 GROUNDING SYSTEM

On the premise that Launch Complex 34 will be used on the SKYLAB Program, it is apparent that a new grounding system is required in this complex. A new design is required which meets the provisions of Volume I of this report, particularly with regard to the provision of single-point grounding and adequate gauge cables which are protected from the effects of EMI. The existing system is in disrepair and the majority of its feeders are inadequate in gauge and EMI protection. Accordingly, a new design and implementation are recommended.

8.7 UPDATING OF MSO BUILDING LIGHTNING PROTECTION SYSTEM

As reported in Section 3 of this volume, there are a number of anomalies in the lightning protection system on the roof of the Manned Spacecraft Operation Building. Aside from loose connections, excessively short cable-bending radii, and dissimilar metal problems, there is the lack of protection of the stile stairs over the A/C duct for the anemometer tower. It is highly recommended that these items be corrected as soon as possible in the interest of personnel and equipment safety.

8.8 DETERMINATION OF LCC (FIRING ROOM) POWER ANOMALY

An anomaly which plagues operations in the LCC firing rooms is a power transient which creates a spike on the 28 Vdc power systems which supply power to several portions of the SA5 vehicle during prelaunch checkout. It is recommended that the source of this transient be located and corrected to preclude potential vehicle damage with the consequent jeopardy of mission success.

8.9 INTERNAL EMI SURVEY OF LC-39

While a number of EMI surveys have been performed for LC-39, those reported in literature have all been concerned with radiated interference with the vehicle and not with the radiated and conducted interference within the complex itself. The experience during the on-site evaluation gained in Room 26E7 with its EMI problem (the power meter which would not zero because of EMI from the TWT modulator) and in the LUT's (the noise on the main ground in Room 3AB induced by power lines adjacent to the ground feeder) leads to the thought that other problems may exist which could be EMI-seated. For example, a problem of false valving in the space vehicle under control of the ACE can only be explained as being the effect of EMI, though the precise mechanism cannot yet be defined. An EMI evaluation program to identify these problems and their sources is, accordingly, recommended.

8.10 CONTINUED ON-SITE GROUNDING SYSTEM EVALUATION

The on-site evaluation effort described in Section 3 of this volume was necessarily limited to a sampling effort because of time limitations and the magnitude of the complex. Only token evaluation could be accomplished in the MSOB, for example. The results from the sampling which was made, however, indicate that further evaluation could reveal anomalies, the removal or correction of which could result in improved overall system performance. The primary areas for continuing effort include the Launch Control Complex for LC-39 (except for the firing rooms) and the MSO Building. Some further effort is required at Pad A, particularly in the service areas. Emphasis on the implementation of grounds in the overall system is the keynote for this additional effort as opposed to consideration of implementation in the individual complexes without regard for the effect of interconnections with other complexes. Accordingly, an evaluation effort to cover the areas not covered in the on-site effort of Section 3 as described above is recommended.

8.11 EMC EVALUATION OF ACE SYSTEM

The recent experience of random false valving which occurred in a spacecraft on the pad during checkout with the ACE system indicates that a detailed EMC analysis of this system is required. The source of this false operation has not been determined positively nor can the problem be voluntarily duplicated. The parity and redundancy built into the coding of the ACE commands almost preclude a false command detection being effected as a result of noise on the MSO pad data link. The problem probably lies in the LUT. It is recommended that an EMC study be initiated which will identify the significant parameters of the system, the points of susceptibility to noise, the possible sources of noise as well as the mechanism by which the noise could affect the susceptible portion of the system. The end product of this study should be the concise definition of the cause of the problem and its solution, backed up by experiment.

8.12 SUMMARY

Implementation of these recommendations can result in significant system performance improvements for the entire LC-39 complex. The effects of common-mode voltages arising from the various compromises described in Section 3 will be minimized. The probability of inadvertent space vehicle damage or malfunction will be reduced, the hazards to personnel will be reduced, and the probability of mission success will be enhanced. Because of the empirical nature of bonding and grounding, it is virtually impossible to assign a value in decibels/dollar of improvement. It has, however, been the experience at other similar installations that corrective action on bonding and grounding yields improvements in system performance.

APPENDIX A

PRELIMINARY MODEL OF GROUNDING SYSTEM

APPENDIX A

PRELIMINARY MODEL OF GROUNDING SYSTEM

A.1 GENERAL

This section presents a point of departure for the development of a model for a wideband grounding system. The basic frequency-dependent equations are developed for the impedance of the several components of a grounding system. These equations should be refined to include the more subtle geological nuances of grounding systems. In addition, criteria will be evolved for matching the impedance of the aboveground portion of the system to the ground plane and belowground portion of the system.

A.2 STATEMENT OF THE PROBLEM

In a typical electrical or electronic installation ground system in an environment of high-rise-time electromagnetic phenomena, such as lightning, the following problems may arise:

a. Pickup of high frequency electromagnetic interference (EMI) by electronic equipment, which is then transmitted to a high surge impedance grounding system

b. Lightning striking a building, resulting in high currents arcing to the building ground cables

c. Lightning striking the earth in the vicinity of the earth ground rods, resulting in arcing directly to the ground cables through the earth

d. Lightning striking the earth some distance from the earth grounding system, causing currents to flow in the remote ground cables through earth conduction

e. Lightning striking from cloud to cloud over the earth grounding system, inducing strong fields in the earth (similar to radiated EMI entering the ground system through the air-earth interface)

The currents and voltages listed above are of importance for the following reasons:

a. Creation of personnel hazards as a result of large chassis potentials, possible equipment explosions, or fires

b. Creation of severe component damage in electronic equipment

c. Disruption of normal equipment operation by introduction of errors and power failure

An analytic model is presented for the portion of the grounding system beneath the earth's surface (see Figure A-1). The model is discussed in reference to the sources of significant grounding problems mentioned.

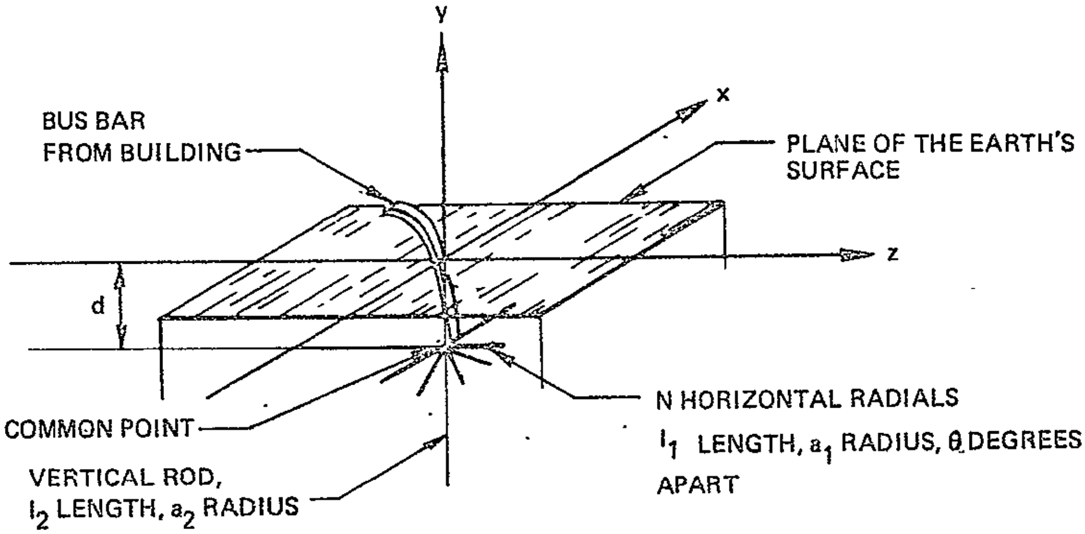


Figure A-1 Grounding System Arrangement, Grounding Below Earth's Surface

A.3 ANALYTIC MODEL

The grounding system to be considered consists of N solid radial cables which are separated θ degrees apart, each of length l_1 and radius a_1. In addition, a driven solid rod of length l_2 and radius a_2 is connected to the vertex of the radials. The building busbar feeds the earth ground rods at this point, which will be called the "common point." The distance d of the counterpoise below the surface is small (approximately 1 ft). The cable lengths l_1 and l_2 are relatively short (about 100 ft or less), but are many times longer than the cable diameters a_1 and a_2 (about 1 inch or less).

For the purposes of this study the grounding cables will be treated as transmission lines buried in a uniform earth. Only induced currents parallel to the cable lengths will be considered. Induced currents perpendicular to the cable will be neglected, as the cable diameters are smaller than any of the wavelengths of interest. The response to sinusoidal fields of frequency ω will be considered, as the transient response to more general time inputs may be evaluated through the customary methods of Fourier analysis (the assumption of system linearity over the frequency range of interest is therefore implied).

The general impedance model is indicated in Figure A-2.

A.3.1 Source Impedance Z_s

Z_s is the impedance of the grounding system as seen from the common point looking back to the aboveground (building) portion of the grounding system. In this study Z_s is taken as the characteristic impedance (Z_o) of a transmission line equivalent to a long rectangular busbar, as shown in Figure A-3 and defined below in Eq. (1).

$$Z_s \doteq Z_o = \left(\frac{R + i\omega L}{G + i\omega c}\right)^{1/2} \tag{1}$$

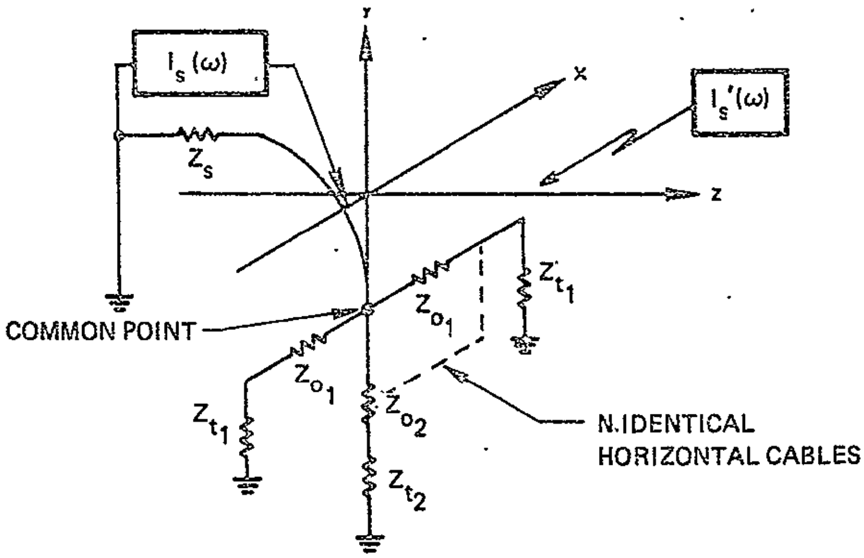


Figure A-2 Impedances of the Grounding System

Typical values for a 2- by 1/4-inch copper busbar are

$$R = 32\ \mu\Omega/\text{ft}$$
$$L = 0.157\ \mu\text{H/ft}$$
$$C = 3.2\ \text{pF/ft}$$
$$G = 10^{-5}\ \text{mho/ft}$$

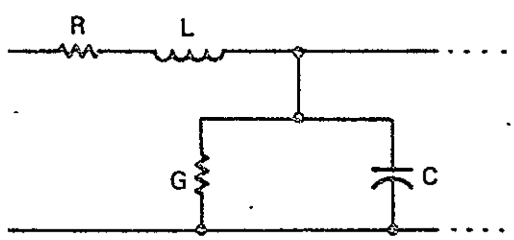


Figure A-3 Busbar Characteristic Impedance

A.3.2 Cable Impedances Z_{o_1} and Z_{o_2}

Sunde (Ref. 1) has shown that mutual impedances occur between the radials of a buried counterpoise. This effect is quite complicated and, as a first approximation, will be neglected. Interaction between the vertical rod and the radial cables

also exists; however, the mutual impedance is greatly reduced due to the perpendicularity of the cables. In the initial model all such mutual impedances will be neglected.

Conductors on Surface of Earth. Marston and Graham (Ref. 2) show that, for a bare conductor on the surface of the earth, the transmission line model of Figure A-4 prevails.

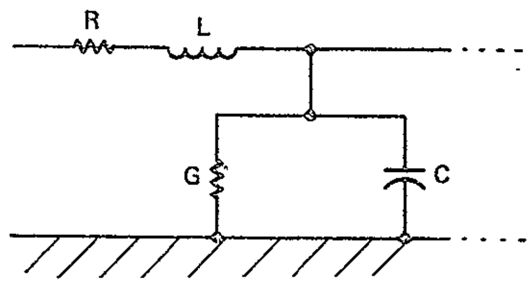


Figure A-4 Model of a Bare Conductor on the Earth's Surface

The parameters of this model in terms of its physical dimensions and electrical constants are defined as follows

$$R = \frac{1}{2\sqrt{2}\pi a}\left(\frac{\omega\mu_c}{\sigma_c}\right)^{1/2} \tag{2}$$

$$L = \frac{\mu_g}{2\pi}\ln\left(\frac{a+\delta_g}{a}\right) + \frac{R}{\omega} \tag{3}$$

$$C = \frac{\pi\epsilon_g}{\ln\left(\frac{a+\delta_g}{a}\right)} \tag{4}$$

$$G = \frac{\pi\sigma_g}{\ln\left(\frac{a+\delta_g}{a}\right)} \tag{5}$$

$$Z_o = \left(\frac{R+i\omega L}{G+i\omega C}\right)^{1/2} \tag{6}$$

$$\Gamma = \left[(R+i\omega L)(G+i\omega C)\right]^{1/2} = \alpha + i\beta \tag{7}$$

$$\alpha = \left[\frac{RG - \omega^2 LC + \sqrt{(RG-\omega^2 LC)^2 + \omega^2(LG+RC)^2}}{2}\right]^{1/2} \tag{8}$$

$$\beta = \left[\frac{\omega^2 LC - RG + \sqrt{(RG - \omega^2 LC)^2 + \omega^2 (LG + RC)^2}}{2}\right]^{1/2} \tag{9}$$

$$v = \omega/\beta \tag{10}$$

where

a = radius of conductor

i = $\sqrt{-1}$

ω = radian frequency ($2\pi f$)

μ_c = conductor magnetic permeability

μ_g = earth magnetic permeability

σ_c = conductivity of conductor

σ_g = conductivity of the earth

ϵ_g = earth dielectric permittivity

δ_g = skin depth in the earth

$= \dfrac{1}{\sqrt{\dfrac{\omega}{2}\mu_g \sigma_g}}$

Z_o = characteristic impedance of equivalent transmission line

Γ = propagation constant of equivalent transmission line

α = attenuation constant

β = phase constant

v = phase velocity of propagation

Conductors Below Surface of Earth. Sunde (Ref. 1) has shown that, for conductors parallel to the earth's surface but a distance below the surface, Eq. (4) (capacitance to ground) and Eq. (5) (conductance to ground) should be modified by replacing the conductor radius a with an equivalent radius a' as follows:

$$a' = (2ad)^{1/2} \tag{11}$$

Therefore, the transmission line parameters for each of the identical radial cables (a distance d below the surface) are taken as:

$$R_1 = \frac{1}{2\sqrt{2}\pi a_1}\left(\frac{\omega\mu_{c_1}}{\sigma_{c_1}}\right)^{1/2} \tag{12}$$

$$L_1 = \frac{\mu_g}{2\pi}\ln\left(\frac{a_1+\delta_g}{a_1}\right) + \frac{R_1}{\omega} \tag{13}$$

$$C_1 = \frac{\pi\epsilon_g}{\ln\left[\frac{(2a_1 d)^{1/2}+\delta_g}{(2a_1 d)^{1/2}}\right]} \tag{14}$$

$$G_1 = \frac{\pi\sigma_g}{\ln\left[\frac{(2a_1 d)^{1/2}+\delta_g}{(2a_1 d)^{1/2}}\right]} \tag{15}$$

$$Z_{o_1} = \left[\frac{R_1 + i\omega L_1}{G_1 + i\omega C_1}\right]^{1/2} \tag{16}$$

$$\Gamma_1 = \left[(R_1 + i\omega L_1)(G_1 + i\omega C_1)\right]^{1/2} \tag{17}$$

where

a_1 = radius of each radial cable

σ_{c_1} = conductivity of each radial cable

μ_{c_1} = magnetic permeability of each radial cable

Whitson and Vance (Ref. 3) state that the equivalent impedances and admittances of a conductor buried 10 diameters or more in the earth are essentially those of a cable buried infinitely deep in the earth. Almost all portions of the vertical ground rod exhibit similar characteristics. Therefore, the equivalent transmission line elements (see Figure A-3) for the vertical rod are:

$$R_2 = \frac{1}{2\sqrt{2}\pi a_2}\left(\frac{\omega\mu_{c_2}}{\sigma_{c_2}}\right)^{1/2} \tag{18}$$

$$L_2 = \frac{\mu_g}{2\pi} \ln\left(\frac{a_2 + \delta_g}{a_2}\right) + \frac{R_2}{\omega} \tag{19}$$

$$C_2 = \frac{2\pi\epsilon_g}{\ln\left(\frac{a_2 + \delta_g}{a_2}\right)} \tag{20}$$

$$G_2 = \frac{2\pi\sigma_g}{\ln\left(\frac{a_2 + \delta_g}{a_2}\right)} \tag{21}$$

$$Z_{o_2} = \left(\frac{R_2 + i\omega L_2}{G_2 + i\omega C_2}\right)^{1/2} \tag{22}$$

$$\Gamma_2 = \left[(R_2 + i\omega L_2)(G_2 + i\omega C_2)\right]^{1/2} \tag{23}$$

where

a_2 = radius of vertical rod

σ_{c_2} = conductivity of vertical rod

μ_{c_2} = magnetic permeability of vertical rod

Note that an assumption implicit in the above equations is that all cables are in good electrical contact with the earth. This is not always the case, especially in areas where the material in the ground is very granular. In such cases small air gaps occur between the cable and the soil. This is equivalent to presence of a dielectric in a coaxial cable (i. e., an additional parallel G and C would have to be added in series with the existing parallel G and C of Figure A-3). Such a conditioi is typical near the surface ($d \leq 2$ ft) where the inherent moisture content is normally quite low.

A. 3. 3 Termination Impedances Z_{t_1} and Z_{t_2}

The impedance terminating the end of a bare wire buried in the earth is to be determined. Marston and Graham (Ref. 2) indicate that this impedance may be taken as

Z_{t_1} = terminating impedance for a radial cable

$$= \frac{1}{2\pi(2a_1 d)^{1/2}(\sigma_g + i\omega\epsilon_g)} \tag{24}$$

$$Z_{t_2} = \text{terminating impedance of a vertical rod}$$
$$= \frac{1}{2\pi a_2 (\sigma_g + i\omega\epsilon_g)} \tag{25}$$

A.4 ANALYSIS EQUATIONS

A.4.1 Currents Transmitted to Ground from Building Busbar

Currents may be introduced by the busbar into the common point (see Figure A-1) as a result of EMI in an equipment building or lightning strokes arcing to the building ground system. These currents $I_S(\omega)$ (see Figure A-1) will be partially reflected back into the building and partially propagated into the earth ground at the common point. The net impedance at the common point (neglecting the earth ground plane) is taken as

$$Z_{\text{common point}} = \frac{Z_V Z_H}{Z_V + Z_H} \tag{26}$$

where

$$Z_H = \text{total impedance of N radial rods}$$
$$= \frac{Z_{o_1}}{N} \left(\frac{Z_{t_1} \cosh \Gamma_1 \ell_1 + Z_{o_1} \sinh \Gamma_1 \ell_1}{Z_{o_1} \cosh \Gamma_1 \ell_1 + Z_{t_2} \sinh \Gamma_1 \ell_1} \right) \tag{27}$$

$$Z_V = \text{impedance of vertical ground rod}$$
$$= Z_{o_2} \left(\frac{Z_{t_2} \cosh \Gamma_2 \ell_2 + Z_{o_2} \sinh \Gamma_2 \ell_2}{Z_{o_2} \cosh \Gamma_2 \ell_2 + Z_{t_2} \sinh \Gamma_2 \ell_2} \right) \tag{28}$$

Equal division of current among the radial rods is assumed in Eq. (27).

As can be seen from Eqs. (26) through (28), the surge impedance of the ground system as seen by currents in the busbar is a complex frequency-dependent quantity which is best calculated by a computer program.

A.4.2 Direct Strikes to Earth Grounding System

Extremely high currents may be experienced should a strike occur directly over the earth ground rods. Almost certainly the lightning channel would arc over to one of the radial ground rods since they are close to the earth's surface. Sunde (Ref. 1) has shown that a stroke may arc to a conductor through about 20 ft of soil. This would be equivalent, analytically, to driving that particular transmission line from a point other than the input. However, since the horizontal rods are relatively short, and since it is known that lightning will tend to strike above-ground protuberances such as antenna towers and launch towers whenever sufficient potential is

generated, it is assumed in this study that a direct strike on the grounding system is unlikely. The postulated cases of a strike to a nearby grounded structure (Paragraph A. 4. 1) and to the earth's surface some distance from the ground rods (Paragraph A. 4. 3) are considered representative problems.

A. 4. 3 Lightning Strikes at a Distance from Earth Grounding System

As shown by Sunde (Ref. 1), the electric intensity in the earth in the vicinity of a buried conductor, resulting from a lightning strike is given by

$$E(\omega, r) = \frac{I_s'(\omega)\rho}{4r^2} \tag{29}$$

where

$I_s'(\omega)$ = lightning current amplitude

ρ = earth's resistivity

r = distance to buried conductor

Thus an E-field is created in the earth which, for high-current strokes, may extend an appreciable distance from the strike point. Sunde assumes a field emanating from the point of contact of the stroke. The component of this field, which is axially directed along each ground rod, will vary as a function of the different orientation of each rod. As a first approximation, the currents induced in each radial rod as a result of this field will be assumed to be proportionally related. The current and voltage at the common point may then be determined from the solutions to the transmission line equations for the vertical and horizontal ground rods. Vance and Nanevicz (Ref. 4) indicate that the general solution for the case of a distributed voltage source along a cable directed along the x axis, resulting from E-fields in the earth (as is the case here) is as follows:

$$I = K_1 e^{\Gamma x} + K_2 e^{-x} + F(x, \omega) \tag{30}$$

$$V = -Z_o \left[\left(K_1 e^{\Gamma x} - K_2 e^{-\Gamma x} + F_v(x, \omega)\right)\right] \tag{31}$$

$$F(x, \omega) = \frac{-1}{2Z_o} \quad e^{\Gamma x}\int e^{-\Gamma x} E(\omega, x)\, dx \; - e^{-\Gamma x}\int e^{\Gamma x} E(\omega, x)\, dx \tag{32}$$

$$F_v(x, \omega) = \frac{1}{\Gamma} \; \frac{\partial F(x, \omega)}{\partial x} \tag{33}$$

where

K_1 and K_2 = constants determined by boundary conditions at x=0 and x=1

$E(\omega, x)$ = voltage/unit length due to fields in the earth

Solution of these complex quantities is laborious and is most readily performed by computer.

A.4.4 EMI Entering Earth Grounding System

E-fields may be induced in the earth as a result of lightning discharges between clouds, or by other sources of EMI such as antenna radiation. The effect of such fields is normally treated in terms of a plane wave incident on the earth. Reflection and transmission of plane waves are discussed extensively by Ramo and Whinnery (Ref. 5). The axially directed portion of the wave which reaches the earth grounding system creates fields equivalent to those discussed in Paragraph A. 1. 3. 3 and is treated in a similar manner.

A. 5 SUMMARY

A general parametric model has been developed for the grounding system of Figure A-1. Specific values of constants (permittivity, conductivity, etc.) may be chosen and inserted into the appropriate equations. Since the values for current and voltage are complex quantities which are functions of frequency and are difficult to manipulate, a computer program should be utilized to calculate the magnitude and phase characteristics of the analytic expressions. Further refinement of the model developed herein would include:

a. Computer programs necessary to obtain numerical results

b. Other mathematical approaches to the solution

c. Effects of ionization due to high surge currents

d. Effects of air gaps between ground rods and soil

e. Variation of earth constants (see Ref. 6), such as permittivity (as a function of earth moisture content and frequency) and conductivity (as a function of ground moisture content, frequency, temperature, soil content, chemical treatment)

f. Effects of stratification and other nonhomogeneities in the earth

A. 6 REFERENCES

1. E. D. Sunde, Earth Conduction Effects in Transmission Systems, D. VanNostrand and Co., Ltd., New York (1949).

2. D. R. Marston and W. R. Graham, Currents Induced in Cables in the Earth by a CW Electromagnetic Field, TR 65-94, Air Force Weapons Lab., Albuquerque, New Mexico.

3. A. L. Whitson and E. F. Vance, Electromagnetic Field Distortions and Currents in and Near Buried Cables and Bunkers, TR 65-39, Final Report on Contract AF 29(601)-5904 with Stanford Research Institute (July 1965).

4. E. F. Vance and J. E. Nanevicz, Internal Voltages and Currents in Solid-Shielded Cables, 1968 IEEE Electromagnetic Compatibility Symposium Record, pp. 381-387.

5. S. Ramo and J. R. Whinnery, Fields and Waves in Modern Radio, 2nd Edition, John Wiley and Sons, Inc., New York (1962).

6. DASA EMP Handbook, DASA Information and Analysis Center, Santa Barbara, California (1968).

APPENDIX B

PROGRAM FOR GROUND CABLE PERFORMANCE CALCULATION

APPENDIX B

COMPUTER MODEL FOR INSTRUMENTATION GROUNDING NETWORK RISER

B.1 INTRODUCTION

A computer program in FORTRAN IV language is developed in this appendix to determine the performance of a ground riser cable installed in ferrous conduit. Some slight modifications of the program language were made to ensure compatibility with the GE Time-Sharing System used to verify the program. These modifications will not, however, cause any perturbation of operation on any computer system.

Included herein is a development of the basic parameters of the grounding cable acting as a quasi-coaxial-cable transmission line, the associated FORTRAN IV program, and a sample printout of the program. The printout lists characteristic impedance, propagation constant, and the performance of the cable when shorted at the connection to the counterpoise. The assumptions for simplifying the calculation are also listed.

B.2 BASIC APPROACH

The characteristic impedance (Z_o) and propagation constant (γ) are determined as a function of frequency for two types of grounding cable inside a vertical ferrous conduit. The relative permeability of the conduit is assumed to be unity over the frequency range under consideration.

$$Z_o = \sqrt{x/y} = \left(\frac{R + j\omega L}{G + j\omega C}\right)^{1/2}$$

where R, L, G, C are per unit line parameters and ω is in radians/sec.

The propagation constant is defined as

$$\gamma = \alpha + j\beta = \sqrt{zy}$$

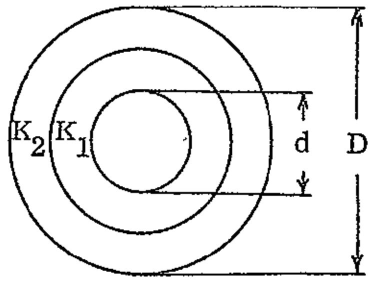
This simplified model is assumed to be a concentric cable with an inner and outer conductor. The inner conductor is one of two types of standard cable and the outer conductor is a steel conduit.

B.3 LINE PARAMETER COMPUTATION

B.3.1 Capacitance (C)

Assume a concentric coaxial type configuration:

$$C = \frac{7.354}{\log_{10}(D/d)} K \qquad \text{pF/ft}$$



where

D	=	inside diameter of outside cylinder
	=	1.61 inches
d	=	outside diameter of inner conductor
	=	0.707 inch
K	=	dielectric constant of material between conductors
K_1	≈	5 for neoprene
K_2	=	1 for air

and neoprene thickness ≈ 0.2 inch

If only air, then K = 1 and hence

$$C = \frac{7.354}{\log_{10}(1.61/0.707)} \times 1 = 20.5 \text{ pF/ft}$$

If only neoprene, then K = 5 and hence

$$C \approx 20.5 \times 5 = 101 \text{ pF/ft}$$

Since the cable is not actually concentric and does touch the sides occasionally, assume C = 50 pF.

B.3.2 Conductance (G)

Calculate the shunt resistance if the cable touches the side of the conduit approximately every 10 ft of the length.

$$\text{Neoprene volume resistivity} = 8 \times 10^{12} \text{ ohm-cm}$$

Assume each contact area covers about 4 cm^2 and neoprene thickness is 0.508 cm. Hence,

$$\text{Volume} = 0.508 \times 4 \approx 2 \text{ cm}^3$$

$$\text{Resistance} = \frac{8 \times 10^{12}}{2} = 4 \times 10^{12} \text{ ohms (every 10 ft)}$$

$$= 4 \times 10^{13} \text{ ohms/ft}$$

$$G = \frac{1}{R} = 0.25 \times 10^{-13} \text{ mho/ft}$$

which is negligible. Hence let G = 0 in the model system.

B.3.3 Inductance (L)

Inductance of a straight wire is

$$L = 0.00508\ell \left(2.303 \log_{10} \frac{4\ell}{d} - 1\right) \qquad \mu H$$

where ℓ is length in inches. For all strands in parallel,

$$L = \frac{1}{N} 0.06096 \left(2.303 \log_{10} \frac{48}{d} - 1\right) \qquad \mu H/ft$$

For standard cable, d = 0.1162 and N = 37; for welding cable, d = 0.0063 and N = 12,691.

For standard,

$$L_s \quad \frac{1}{37} \times 0.06096 \left(2.303 \log_{10} \frac{48}{0.1162} - 1\right)$$

$$1.65 \times 10^{-3} (5.1) \approx 8.4 \times 10^{-9} \qquad H/ft$$

For welding.

$$L_w \quad \frac{1}{12,691} \times 0.06906 \left(2.303 \log_{10} \frac{48}{0.0063} - 1\right)$$

$$= 4.8 \times 10^{-6} (7.94) \approx 38 \times 10^{-12} \qquad H/ft$$

B.3.4 Resistance (R)

Calculate the ac resistance as a function of frequency, using the parameters developed as defined for the cables under consideration.

$$R_{ac} = \frac{\rho \ell}{NA} \times \frac{2.54 \text{ (cm/inch)}}{(2.54)^2} \quad \text{ohms/ft}$$

where

ρ = copper resistivity

= 1.724×10^{-6} ohm-cm

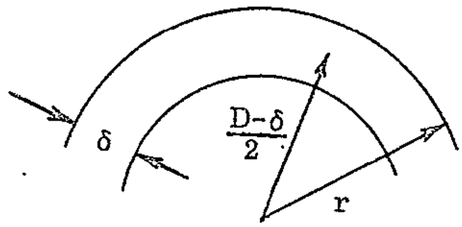
ℓ = length = 12 inches

A = cross-sectional area (in^2)

= $\delta \times \frac{D - \delta}{2} \times \Theta$

with $D = 2r$

δ = skin depth (inches)



θ = outer angle between points which are tangent to adjacent outer layer conductors

$$R_{ac} \approx \frac{\rho\ell}{2.54\ AN} = \frac{\rho\ell}{N(2.54)\delta\Theta\frac{D-\delta}{2}} = \frac{2\rho\ell}{2.54\Theta N} \cdot \frac{1}{D\delta - \delta^2}$$

For 500 MCM standard power cable,

$\Theta = 2\pi \times \frac{200}{360} = 3.49$ rad

N = 18 strands

D = 0.1162 inch

For 500 MCM welding cable,

$\Theta = 2\pi \times \frac{180}{360} = 3.141$ rad

N = 350 strands

D = 0.0063 inch

$$R_{ac}\,(\text{Std}) = \frac{(2)(1.724)(12)}{(2.54)\ (3.48)} \times 10^{-6}\ \frac{1}{D\delta - \delta^2} = \frac{0.26 \times 10^{-6}}{0.1162\,\delta - \delta^2}\ \text{ohm/ft}$$

$$R_{ac}\,(\text{Welding}) = \frac{(2)(1.724)(12)}{(2.54)\ (3.14)} \times 10^{-6}\ \frac{1}{D\delta - \delta^2} = \frac{3.852 \times 10^{-8}}{0.0063\,\delta - \delta^2}\ \text{ohm/ft}$$

Thus

$\delta = \frac{2.6}{\sqrt{f}}$ (inch) for copper

B.4 COMPUTER PROGRAM

The equations and parameters derived or defined above are now converted into FORTRAN IV language for computation of Z_0, γ , and Z_{ref} versus frequency. The program is written as follows.

```
10 FUNCTION CMULT(U,V,X,Y)
20 X1 = X
30 X = U*X - V*Y
40 Y = V*X1 + U*Y
50 CMULT = X
60 RETURN
70 END
80 FUNCTION CDIV(U,V,X,Y)
90 D = X*X + Y*Y
100 Y = -Y
110 X = CMULT(U,V,X,Y)/D
120 Y = Y/D
130 CDIV = X
140 RETURN
150 END
160 FUNCTION CSQRT(U,V)
170 FAC = SQRT(SQRT(U*U + V*V))
180 ANG = ATAN2(V,U)/2.0
190 U = FAC * COS(ANG)
200 V = FAC * SIN(ANG)
210 CSQRT = U
220 RETURN
230 END
240 FUNCTION TRSG(FRAD,R,H,G,C,ALPHA,BETA)
250 FRAD2 = FRAD * FRAD
260 FAC1 = R * G - FRAD2 * C * H
270 FAC2 = FRAD *(G * H + R * C)
280 ALPHA = CSQRT(FAC1,FAC2)
290 BETA = FAC2
300 TRSG = ALPHA
310 RETURN
320 END
330 FUNCTION CHARZ(FRAD,R,H,G,C,R0,X0)
340 GG = G
350 X = FRAD* H
360 B = FRAD * C
370 FAC1 = CDIV(R,X,GG,B)
380 R0 = CSQRT(FAC1,B)
390 X0 = B
400 CHARZ = R0
410 RETURN
420 END
```

```
      FUNCTION CTANH(U,V)
      A=TANH(U)
      B=TAN(V)
      A2=A*A
      B2=B*B
      D=1.0+A2*B2
      U=A*(1.0+B2)/D
      V=B*(1.0-A2)/D
      CTANH=U
    RETURN
     END
     FUNCTION ZREFL(RL,XL,ALPHA,BETA,R0,X0,RREFL,XREFL)
     A=ALPHA
     B=BETA
     RR0=R0
     XX0=X0
     XNUM=CDIV(RL,XL,RR0,XX0)+CTANH(A,B)
     YNUM=XX0+B
    XDEN=1.0+CMULT(RR0,XX0,A,B)
     YDEN=B
     XINN=CDIV(XNUM,YNUM,XDEN,YDEN)
     RREFL = CMULT(R0,X0,XINN,YDEN)
     XREFL = YDEN
     ZREFL = RREFL
     RETURN
     END
     PRINT 10
 10  FORMAT(1H0,"THIS PROGRAM COMPUTES AN APPROXIMATE VALUE
& OF CHARACTERISTIC"/1X"IMPEDANCE VS FREQUENCY FOR TWO WIRE
& TYPES,500 MCM STD POWER"/1X,"CABLE (37 STRANDS) AND 500 MCM
& WELDING CABLE (12,961 STRANDS)"/1X,",THE SECOND SET OF DATA
& IS THE PROPAGATION CONSTANT FOR SAME")
*    DIA= DIAMETER OF A SINGLE WIRE STRAND
*     CAP= EST. CABLE CAPACITANCE MICROMICROFARAD/FOOT
*     COIL= EST. AC--CABLE SELF INDUCTANCE , MICROHY/FOOT
*     DEL= SKIN DEPTH
*     RES= AC RESISTANCE
*     G= CONDUCTANCE MHO/FOOT
     A=0
     B=0.0
     C=0.0
     C1=0.26E-6
     C2=3.85E-8
     C3= .1162
     C4=0.0063
     C5=50.0E-12
     C6=8.4E-9
     C7=3.5E-11
     C8=0.0
     C9=0.0
```

```
930   15  CONTINUE
940       CON=C1
950       DIA=C3
960       CAP=C5
970       COIL=C6
980       G=C8
990       K=1
1000  20   GO TO 40
1010  30   CONTINUE
1020       CON=C2
1030       DIA=C4
1040       COIL=C7
1050       G=C9
1060       A=1.0
1070       K=2
1080  40   CONTINUE
1100       IF(C.EQ.1.0) GO TO 170
1110       IF(B.EQ.1.0) GO TO 110
1120       PRINT 50
1130  50   FORMAT(1H-,"FREQUENCY(MHZ)",4X,"CHAR IMPEDANCE(OHMS)",
1140&     4X,"AC RES(MOHMS)",4X,"SK DP(IN)"/23X,"REAL",5X,"IMAG")
1150       GO TO 130
1160 110   PRINT 120
1170 120   FORMAT(1H-,"FREQUENCY(MHZ)",4X,"PROPAGATION CONSTANT",
1180&      4X,"AC RES(MILOHM)",4X,"SK DP(IN)"/18X,"ALPHA(DB)",
1190&      2X,"BETA(RAD)")
1200       GO TO 130
1210  170  PRINT: "CABLE LENGTH DESIRED,FEET"
1220       READ: FEET
1230       PRINT 180
1240  180  FORMAT(1H-,"FREQUENCY(MHZ)",4X,"RREFL",6X,"XREFL")
1250       GO TO 130
1260 130   DO 60 N=K,6
1270       DO 70 I=2,10,2
1280       FREQ=FLOAT(I)*1.0E3*10.0**FLOAT(N)
1290       FRAD=6.28318*FREQ
1300      DEL=2.6/SQRT(FREQ)
1310      RES=CON/(DIA*DEL-DEL**2)
1320       IF(C.EQ.1.0) GO TO 190
1330      IF(B.EQ.1.0) GO TO 150
1340       CALL CHARZ(FRAD,RES,COIL,G,CAP,ZR,ZM)
1350      PRINT 80,(FREQ/1.0E+6),ZR,ZM,(RES*1.0E+3),DEL
1360 80   FORMAT(3X,F7.2,11X,F7.3,2X,F7.3,8X,F7.3,10X,E8.2)
1370      GO TO 70
```

```
1380 150 CALL TRSG(FRAD,RES,COIL,G,CAP,ZR,ZM)
1390     PRINT 160,(FREQ*1.0E-6),(ZR*8.686),ZM,(RES*1.0E+3),DEL
1400 160 FORMAT(3X,F8.2,7X,F7.3,4X,F7.3,8X,F7.3,9X,E8.2)
1405     GO TO 70
1410 190 CALL TRSG(FRAD,RES,COIL,G,CAP,ZA,ZB)
1420     CALL CHARZ(FRAD,RES,COIL,G,CAP,ZR,ZM)
1430     CALL ZREFL(0.0,0.0,ZA*FEET,ZB*FEET,ZR,ZM,RREFL,XREFL)
1440     PRINT 200,FREQ*1.0E-6,RREFL,XREFL
1450 200 FORMAT(3X,F8.2,6X,F7.3,4X,F7.3)
1460 70  CONTINUE
1470 60  CONTINUE
1500     IF(A.EQ.1.0) GO TO 100
1510     GO TO 30
1520 100 CONTINUE
1530     IF(B.EQ.1.0) GO TO 140
1540     B=1.0
1550     A=0.0
1560     GO TO 15
1570 140 CONTINUE
1580     A=0.0
1590     IF(C.EQ.1.0) GO TO 210
1600     C=1.0
1610     GO TO 15
1620 210 END

READY

*1090
*1480
*1490
*RUN
```

B.5 COMPUTER PROGRAM LISTINGS

Using the program defined in Paragraph B.4, the characteristics of 500 MCM standard power cable and 500 MCM welding cable were computed as a function of frequency.

B.5.1 Listing of Approximate Value of Characteristic Impedance vs Frequency for 500 MCM, 37 Strand, Power Cable (See Note 1)

FREQUENCY(MHZ)	CHAR IMPEDANCE(OHMS)		AC RES(MOHMS)	SK DP(IN)
	REAL	IMAG		
0.02	12.992	-0.886	0.145	0.18E-01
0.04	12.975	-0.594	0.194	0.13E-01
0.06	12.970	-0.474	0.232	0.11E-01
0.08	12.968	-0.406	0.264	0.92E-02
0.10	12.966	-0.359	0.293	0.82E-02
0.20	12.964	-0.249	0.405	0.58E-02
0.40	12.963	-0.173	0.564	0.41E-02
0.60	12.962	-0.140	0.686	0.34E-02
0.80	12.962	-0.121	0.789	0.29E-02
1.00	12.962	-0.108	0.880	0.26E-02
2.00	12.962	-0.076	1.237	0.18E-02
4.00	12.962	-0.053	1.741	0.13E-02
6.00	12.962	-0.044	2.127	0.11E-02
8.00	12.962	-0.038	2.454	0.92E-03
10.00	12.962	-0.034	2.741	0.82E-03
20.00	12.962	-0.024	3.868	0.58E-03
40.00	12.961	-0.017	5.462	0.41E-03
60.00	12.961	-0.014	6.685	0.34E-03
80.00	12.961	-0.012	7.717	0.29E-03
100.00	12.961	-0.011	8.625	0.26E-03
200.00	12.961	-0.007	12.190	0.18E-03
400.00	12.961	-0.005	17.231	0.13E-03
600.00	12.961	-0.004	21.099	0.11E-03
800.00	12.961	-0.004	24.360	0.92E-04
1000.00	12.961	-0.003	27.233	0.82E-04
2000.00	12.961	-0.002	38.506	0.58E-04
4000.00	12.961	-0.002	54.447	0.41E-04
6000.00	12.961	-0.001	66.680	0.34E-04
8000.00	12.961	-0.001	76.992	0.29E-04
0000.00	12.961	-0.001	86.078	0.26E-04

B. 5. 2 Listing of Approximate Value of Characteristic Impedance vs Frequency for 500 MCM, 12,691 Strand, Welding Cable (See Note 1)

FREQUENCY(MHZ)	CHAR IMPEDANCE(OHMS) REAL	IMAG	AC RES(MOHMS)	SK DP(IN)
0.20	10.427	-10.394	13.620	0.58E-02
0.40	4.168	-4.084	4.278	0.41E-02
0.60	3.270	-3.161	3.897	0.34E-02
0.80	2.850	-2.725	3.903	0.29E-02
1.00	2.594	-2.455	4.002	0.26E-02
2.00	2.025	-1.844	4.694	0.18E-02
4.00	1.653	-1.426	5.923	0.13E-02
6.00	1.490	-1.233	6.924	0.11E-02
8.00	1.392	-1.112	7.784	0.92E-03
10.00	1.325	-1.027	8.548	0.82E-03
20.00	1.156	-0.797	11.580	0.58E-03
40.00	1.036	-0.611	15.903	0.41E-03
60.00	0.984	-0.518	19.231	0.34E-03
80.00	0.954	-0.459	22.040	0.29E-03
100.00	0.935	-0.417	24.516	0.26E-03
200.00	0.891	-0.306	34.239	0.18E-03
400.00	0.865	-0.221	47.999	0.13E-03
600.00	0.856	-0.181	58.560	0.11E-03
800.00	0.851	-0.158	67.465	0.92E-04
1000.00	0.849	-0.141	75.310	0.82E-04
2000.00	0.843	-0.100	106.093	0.58E-04
4000.00	0.840	-0.071	149.630	0.41E-04
6000.00	0.839	-0.058	183.039	0.34E-04
8000.00	0.838	-0.050	211.203	0.29E-04
0000.00	0.838	-0.045	236.017	0.26E-04

B. 5. 3 Listing of Approximate Value of Propagation Constant, AC Resistance, and Skin Depth vs Frequency for 500 MCM 37 Strand Power Cable (See Note 1)

FREQUENCY(MHZ)	PROPAGATION CONSTANT ALPHA(DB)	BETA(RAD)	AC RES(MILOHM)	SK DP(IN)
0.02	0.000	0.000	0.145	0.18E-01
0.04	0.000	0.000	0.194	0.13E-01
0.06	0.000	0.000	0.232	0.11E-01
0.08	0.000	0.000	0.264	0.92E-02
0.10	0.000	0.000	0.293	0.82E-02
0.20	0.000	0.001	0.405	0.58F-02
0.40	0.000	0.002	0.564	0.41E-02
0.60	0.000	0.002	0.686	0.34E-02
0.80	0.000	0.003	0.789	0.29E-02
1.00	0.000	0.004	0.880	0.26E-02
2.00	0.000	0.008	1.237	0.18E-02
4.00	0.001	0.016	1.741	0.13E-02
6.00	0.001	0.024	2.127	0.11E-02
8.00	0.001	0.033	2.454	0.92E-03
10.00	0.001	0.041	2.741	0.82E-03
20.00	0.001	0.081	3.868	0.58E-03
40.00	0.002	0.163	5.462	0.41E-03
60.00	0.002	0.244	6.685	0.34E-03
80.00	0.003	0.326	7.717	0.29E-03
100.00	0.003	0.407	8.625	0.26E-03
200.00	0.004	0.814	12.190	0.18E-03
400.00	0.006	1.629	17.231	0.13E-03
600.00	0.007	2.443	21.099	0.11E-03
800.00	0.008	3.258	24.360	0.92E-04
1000.00	0.009	4.072	27.233	0.82E-04
2000.00	0.013	8.144	38.506	0.58E-04
4000.00	0.018	16.288	54.447	0.41E-04
6000.00	0.022	24.432	66.680	0.34E-04
8000.00	0.026	32.576	76.992	0.29E-04
10000.00	0.029	40.720	86.078	0.26E-04

B. 5. 4 Listing of Approximate Value for Propagation Constant, AC Resistance and Skin Depth vs Frequency for 500 MCM 12, 691 Strand Welding Cable (See Note 1)

FREQUENCY(MHZ)	PROPAGATION CONSTANT		AC RES(MILOHM)	SK DP(IN)
	ALPHA(DB)	BETA(RAD)		
0.20	0.006	0.001	13.620	0.58E-02
0.40	0.004	0.001	4.278	0.41E-02
0.60	0.005	0.001	3.897	0.34E-02
0.80	0.006	0.001	3.903	0.29E-02
1.00	0.007	0.001	4.002	0.26E-02
2.00	0.010	0.001	4.694	0.18E-02
4.00	0.016	0.002	5.923	0.13E-02
6.00	0.020	0.003	6.924	0.11E-02
8.00	0.024	0.003	7.784	0.92E-03
10.00	0.028	0.004	8.548	0.82E-03
20.00	0.044	0.007	11.580	0.58E-03
40.00	0.067	0.013	15.903	0.41E-03
60.00	0.085	0.019	19.231	0.34E-03
80.00	0.100	0.024	22.040	0.29E-03
100.00	0.114	0.029	24.516	0.26E-03
200.00	0.167	0.056	34.239	0.18E-03
400.00	0.241	0.109	47.999	0.13E-03
600.00	0.297	0.161	58.560	0.11E-03
800.00	0.344	0.214	67.465	0.92E-04
1000.00	0.385	0.267	75.310	0.82E-04
2000.00	0.547	0.529	106.093	0.58E-04
4000.00	0.774	1.055	149.630	0.41E-04
6000.00	0.948	1.581	183.039	0.34E-04
8000.00	1.094	2.107	211.203	0.29E-04
10000.00	1.223	2.632	236.017	0.26E-04

B.5.5 Listing of Approximate Value of Reflection Coefficient for 100 Feet of 500 MCM 37 Strand Power Cable with Shorted Receiver (See Note 1)

CABLE LENGTH DESIRED, FEET
= 100.0

FREQUENCY(MHZ)	RREFL	XREFL
0.02	0.014	0.106
0.04	0.019	0.211
0.06	0.023	0.317
0.08	0.026	0.422
0.10	0.029	0.528
0.20	0.041	1.058
0.40	0.057	2.130
0.60	0.071	3.231
0.80	0.085	4.378
1.00	0.099	5.590
2.00	0.212	13.735
4.00	24.647	220.361
6.00	0.145	-10.881
8.00	0.129	1.510
10.00	0.429	17.387
20.00	2.280	-43.327
40.00	0.401	8.484
60.00	0.560	-10.926
80.00	2.432	29.575
100.00	0.436	-1.575
200.00	0.644	-3.193
400.00	1.094	-6.779
600.00	1.870	-11.378
800.00	3.708	-18.343
1000.00	10.124	-31.590
2000.00	3.332	10.951
4000.00	45.620	27.008
6000.00	9.208	-15.858
8000.00	3.980	-3.131
10000.00	5.053	5.643

B. 5. 6 Listing of Approximate Value of Reflection Coefficient for 100 Feet of 500 MCM 12, 691 Strand Welding Cable with Shorted Receiver (See Note 1)

CABLE LENGTH DESIRED, FEET
= 100.0

FREQUENCY(MHZ)	RREFL	XREFL
0.20	1.362	0.001
0.40	0.428	0.008
0.60	0.390	0.012
0.80	0.390	0.016
1.00	0.400	0.020
2.00	0.470	0.039
4.00	0.596	0.073
6.00	0.702	0.102
8.00	0.798	0.125
10.00	0.887	0.143
20.00	1.294	0.125
40.00	1.660	-0.523
60.00	1.133	-0.842
80.00	0.832	-0.627
100.00	0.796	-0.412
200.00	0.870	-0.340
400.00	0.872	-0.221
600.00	0.855	-0.180
800.00	0.851	-0.158
1000.00	0.849	-0.141
2000.00	0.843	-0.100
4000.00	0.840	-0.071
6000.00	0.839	-0.058
8000.00	0.838	-0.050
10000.00	0.838	-0.045

NOTE 1: The effects of mutual conductance and mutual inductance between conductors were neglected for the purpose of this computer run. Therefore, results above 1 MHz are not completely accurate but are a close enough approximation for formulation of system design criteria.

APPENDIX C

ELECTROMAGNETIC COMPATIBILITY GUIDELINES

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ELECTROMAGNETIC COMPATIBILITY GUIDELINES

This appendix discusses techniques for achieving electromagnetic compatibility (EMC) when bonding and grounding alone are not sufficiently effective. These guidelines are based on theoretical considerations as well as on a decade of experience with satellite tracking and communication stations located throughout the world.

A typical station covers the full spectrum of potential EMI - frequencies ranging from 1 Hz in the timing generator to 32 GHz in paramp pump signals, and power levels from -110 dBm (downlink S-band received power) through typical logic levels at 6V, 1 to 10 mA up to the 10 to 12 kW CW power output of command transmitters. In such a station the equipments having these operating levels and frequencies are closely contained, often within a single building. Clearly, if EMC is to be achieved in such a complex, highly compressed installation, EMC design must be treated carefully and from a systems standpoint. The KSC launch complexes include a similar set of EMC design problems, and the satellite communication and tracking station experience is most apropos to these installations.

Careful attention to grounding system details and rigorous enforcement of bonding and grounding disciplines during the design, fabrication, and installation of a system, subsystem, or total complex are essential in providing for EMC. Experience has repeatedly proven how very necessary it is if a complex electronic system is to function as designed. Proper bonding and grounding are indeed effective in practice in solving a class of otherwise insidious EMI problems.

The guidelines and criteria contained in this appendix are a part of the disciplines established for incorporating an effective bonding and grounding system into the design of new ground stations as well as for additions to existing stations. Application of these ground rules and criteria starts with the earliest system design concepts in facilities and equipment layout.

This is not to say that bonding and grounding are a panacea for the solution of all EMC problems - many remain which must be treated by other techniques. These other techniques are filtering, shielding, system and cabling layout, and circuit design disciplines to minimize susceptibility to EMI from any source, be it internal or external to the system.

The following discussions contain a brief treatment of EMC techniques other than bonding and grounding.

C.1 FILTERING

A filter, in this context, is defined as an electrical network designed to offer a low attenuation over a desired range of frequencies and a high attenuation outside of that range. In achieving EMC, filters are used for two purposes:

a. To contain potentially interfering signals within their source to preclude their degrading the performance of susceptible circuits.

b. To prevent potentially interfering signals from entering susceptible circuits where they could degrade the circuit's performance.

The characteristics to be considered in filter selection are:

- Attenuation vs frequency
- Impedance matching
- Voltage and current rating
- Voltage drop
- Insertion loss in passband
- Insulation resistance
- Mounting and connecting details
- Size and weight
- Cost and cost effectiveness

How and where filters may be inserted is a basic decision in system design. Some rules regarding filter use are as follows:

a. Avoid redundancy in filtering a given circuit; e.g., a filter in the power line to an enclosure, as well as its power distribution panel, constitutes redundant filtering.

b. Select power filters for a current rating at 133% of the load. This provides a balance between providing an impedance match and still operating below the inductor saturation point. Filters of this type are designed for their rated attenuation characteristic when terminated in a 50-ohm resistive load, and current capacity is the only characteristic by which the filter may be matched to its load.

c. Adjust the power factor of the load to no less than 90%. Resonant effects occur in filters working into a reactive load, which result in excessive voltage drops across the filters.

d. Place filters in the lines of an EMI source device if many susceptible circuits could be degraded by the source.

e. Place filters in the lines of susceptible devices when only a few of these devices could be degraded by a source or sources.

C.2 SHIELDING

One of the most effective means of preventing degradation of system performance from radiated EMI is the use of shielding. Adequate selection and application of

shielding for chassis, enclosures, cabling, and rooms will minimize the effects of interference generated within a system and the degradation of the performance of susceptible circuits.

Shielding effectiveness is defined as the total attenuation of radiated electromagnetic energy realized when the energy attempts to penetrate a barrier or shield. Shielding effectiveness, in decibels, is

$$10 \log_{10} \frac{\text{power density outside barrier}}{\text{power density inside barrier}}$$

and is made up of three factors

$$SE = R + A + K$$

where

R = reflection loss from surface, dB

A = absorption loss in shield material, dB

K = correction factor for internal reflection within shield material, dB (insignificant in metal walls of usual thickness)

Absorption loss may be calculated from the following equation or from nomographs C-1 and C-2

$$A = 3.338\ T \sqrt{f \sigma_r \mu}$$

where

T = wall thickness, mils

f = frequency, MHz

σ_r = wall conductivity relative to copper

μ = wall relative permeability

For plane waves (E/H = 377 ohms), magnetic materials provide the best absorption loss (since $\mu \gg \sigma$) and good conductors provide the best reflection loss (since $\sigma \gg \mu$ and the loss is proportional to σ/μ). Remember that in magnetic materials, μ is frequency dependent and approaches unity at frequencies above 100 kHz.

The incident field impinging upon a shield may be a plane wave if the source is greater than 5 wavelengths from the shield. Where this distance is less than 5 wavelengths away, the E-field or H-field may predominate depending on the propagation mode and impedance. An E-field is one in which the electric field intensity vector predominates. This type of field is also referred to as a high-impedance

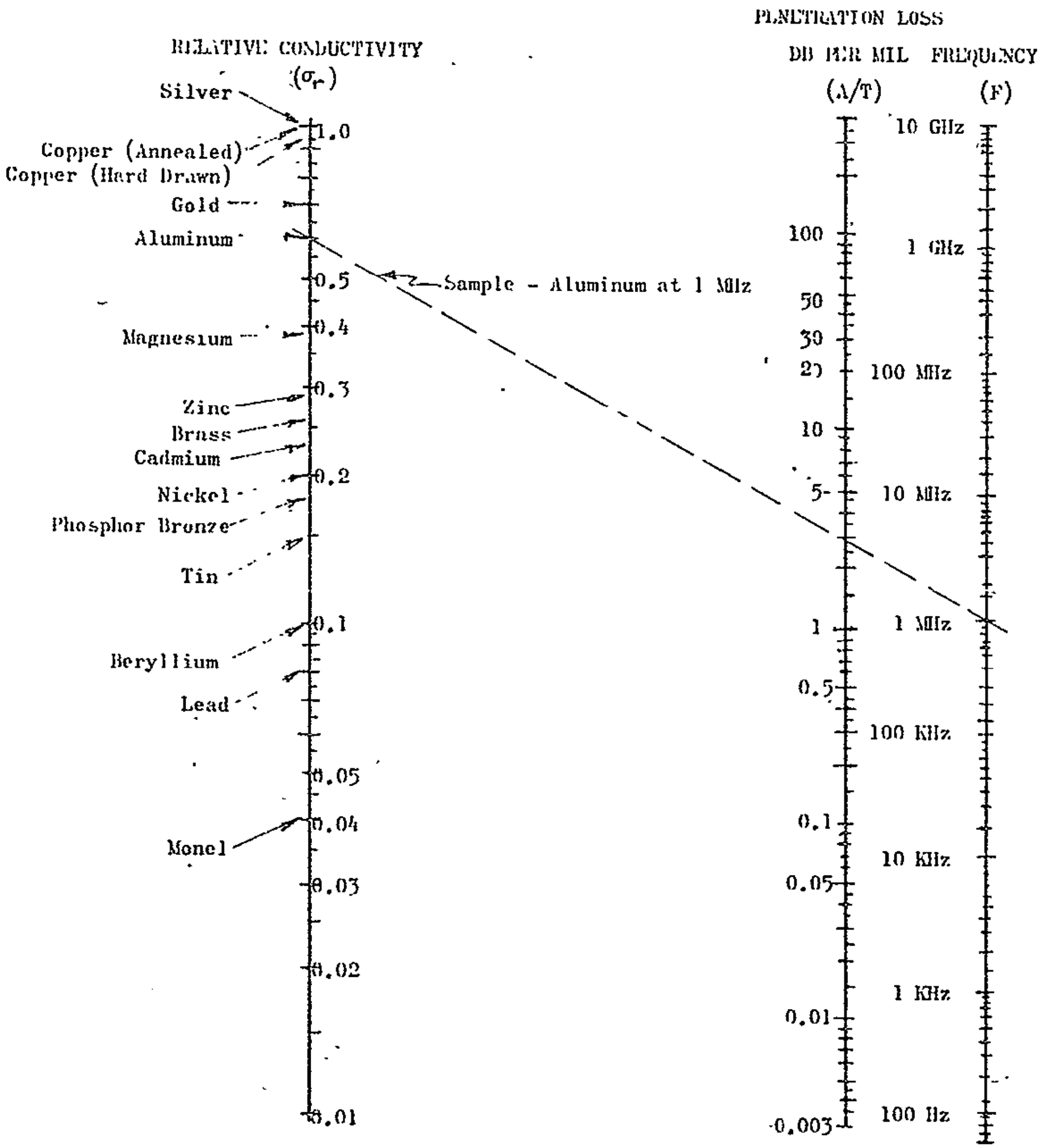

Figure C-1 Nomograph for Absorption or Penetration Loss of Solid Nonmagnetic Materials

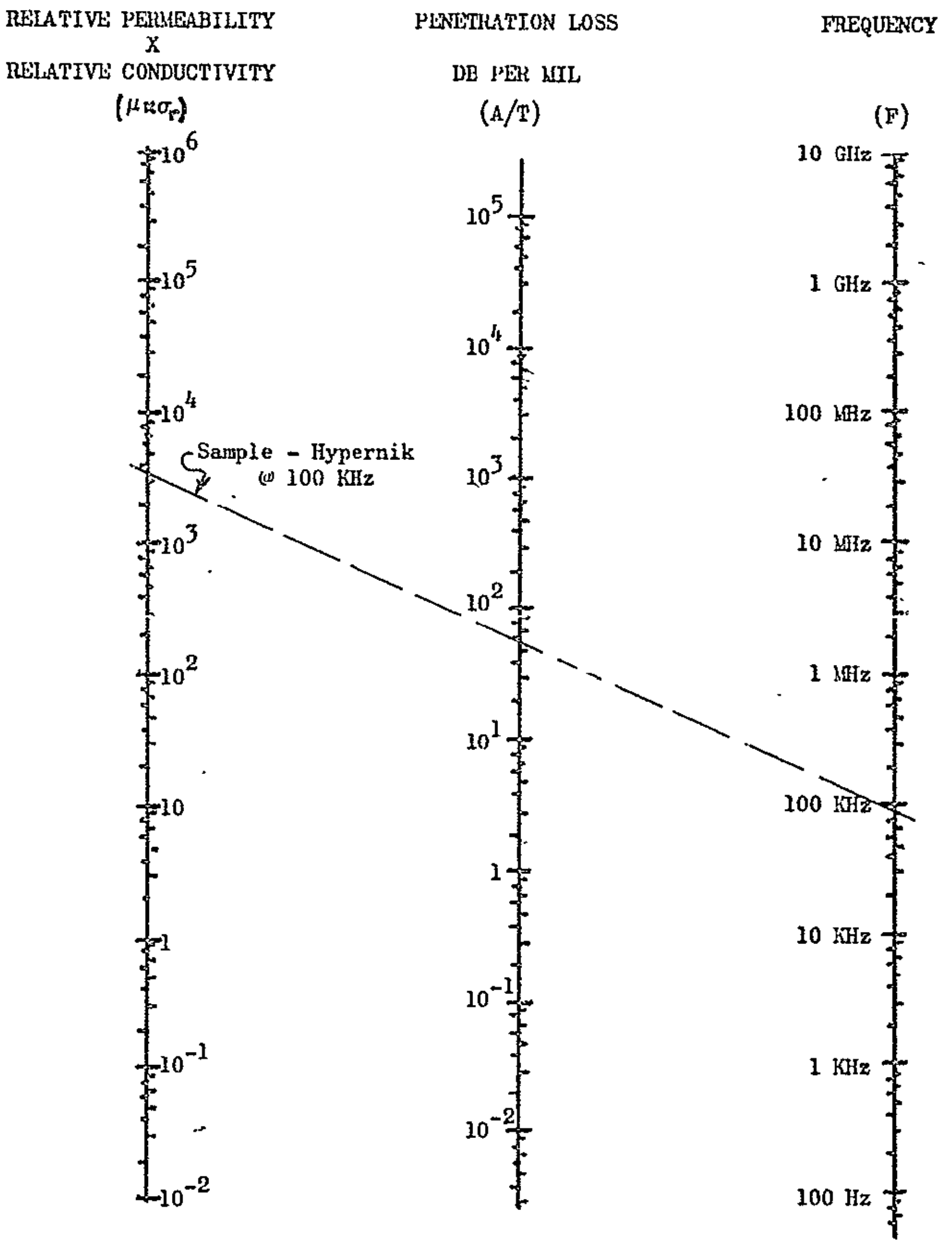

Figure C-2 Nomograph for Absorption or Penetration Loss of Solid Magnetic and Nonmagnetic Materials

field (E/H > 377 ohms). An H-field is one in which the magnetic field intensity vector predominates and is referred to as a low-impedance field (E/H < 377 ohms) The reflection loss is different for each of these three waves or fields.

For a plane wave the reflection loss is given as

$$R_p = 168.2 + 10 \log_{10} \left(\frac{\sigma_r}{\mu f}\right)$$

where

R_p = plane wave reflection loss, dB

σ_r = conductivity relative to copper

μ = relative permeability

f = frequency, Hz

For an electric field the reflection loss is

$$R_E = 353.6 + 10 \log_{10} \left(\frac{\sigma_r}{f^3 \mu_r^2}\right)$$

where R_E is the E-field reflection loss, in decibels.

In the case of a magnetic field, the reflection is

$$R_H = 20 \log_{10} \left[\left(\frac{0.462}{r} \cdot \frac{\mu}{f\sigma_r}\right)^{1/2} + 0.136r \left(\frac{\mu}{f\sigma_r}\right)^{1/2} + 0.354\right]$$

where

R_H = H-field reflection loss, dB

r = distance from source, inches

Table C-1 lists the relevant characteristics of various metals used for shields. Figures C-3 through C-8 present the information in the form of nomographs.

In the implementation of shielding to obtain optimum shielding effectiveness, careful attention must be given to the following items:

- Seam bonding (should be continuous seam weld)
- Use of RF gaskets around doors and panels
- Control of radiation through apertures

- Use of metal finger stock around doors
- Use of bonds across hinges
- Prevention of leakage around bolts and/or rivets
- Potential corrosion areas in joints
- Points of potential mechanical wear
- Care to prevent unevenness

C.3 CABLING

Various factors must be considered in reducing both inductive and capacitive coupling of EMI between cables, including as a partial list the following:

- Frequency and bandwidth of associated circuitry
- Filtering applied on cable circuits
- Reduction of exposure to pickup
- Reduction of loop area
- Separation of loops
- Orthogonal orientation of adjacent loops
- Internal transposition of loop conductors
- Adequate shielding of cables
- Adequate shielding of conductors
- Correct grounding of cable shields

Additional ground rules are:

- Run signal and control lines in twisted pair, using second wire for return.
- Minimize common mode voltages by ensuring minimum impedance in common portions of the grounding system.
- Separate high and low level cables in all runs.
- Ground spare conductors at end of cable at which shield is grounded.
- Use cable with insulating jackets to preclude ground compromise.
- Never use shields and other ground conductors for circuit returns (except for coaxial cables).
- Ground shields of cables with low-level signal (< 0.5 V rms) at receiving end.
- Ground shields of cables with high-level signals (> 0.5 V rms) at sending end.

TABLE C-1

CHARACTERISTICS OF VARIOUS METALS USED FOR SHIELDS

Metal	Relative Conductivity	Relative Permeability at 150 kHz	Penetration Loss (dB/mil at 150 kHz)
Silver	1.05	1	1.32
Copper-Annealed	1.00	1	1.29
Copper-Hard Drawn	0.97	1	1.26
Gold	0.70	1	1.08
Aluminum	0.61	1	1.01
Magnesium	0.38	1	0.79
Zinc	0.29	1	0.70
Brass	0.26	1	0.66
Cadmium	0.23	1	0.62
Nickel	0.20	1	0.58
Phosphor-Bronze	0.18	1	0.55
Iron	0.17	1,000	16.9
Tin	0.15	1	0.50
Steel, SAE 1045	0.10	1,000	12.9
Beryllium	0.10	1	0.41
Lead	0.08	1	0.36
Hypernick	0.06	80,000	88.5
Monel	0.04	1	0.26
Mu-Metal	0.03	80,000	63.2
Permalloy	0.03	80,000	63.2
Steel, Stainless	0.02	1,000	5.7

Relative conductivity $\sigma_r = \sigma_x/\sigma_c$

where σ_x = absolute conductivity of material

σ_c = absolute conductivity of copper

1.742×10^{-6} ohm-cm (CGS)

1.742×10^{-8} ohm-meter (MKS)

Relative permeability $\mu = \mu_x/\mu_o$

where μ_x = absolute permeability of material

$\mu_o = 4\pi \times 10^{-7}$ henry/meter

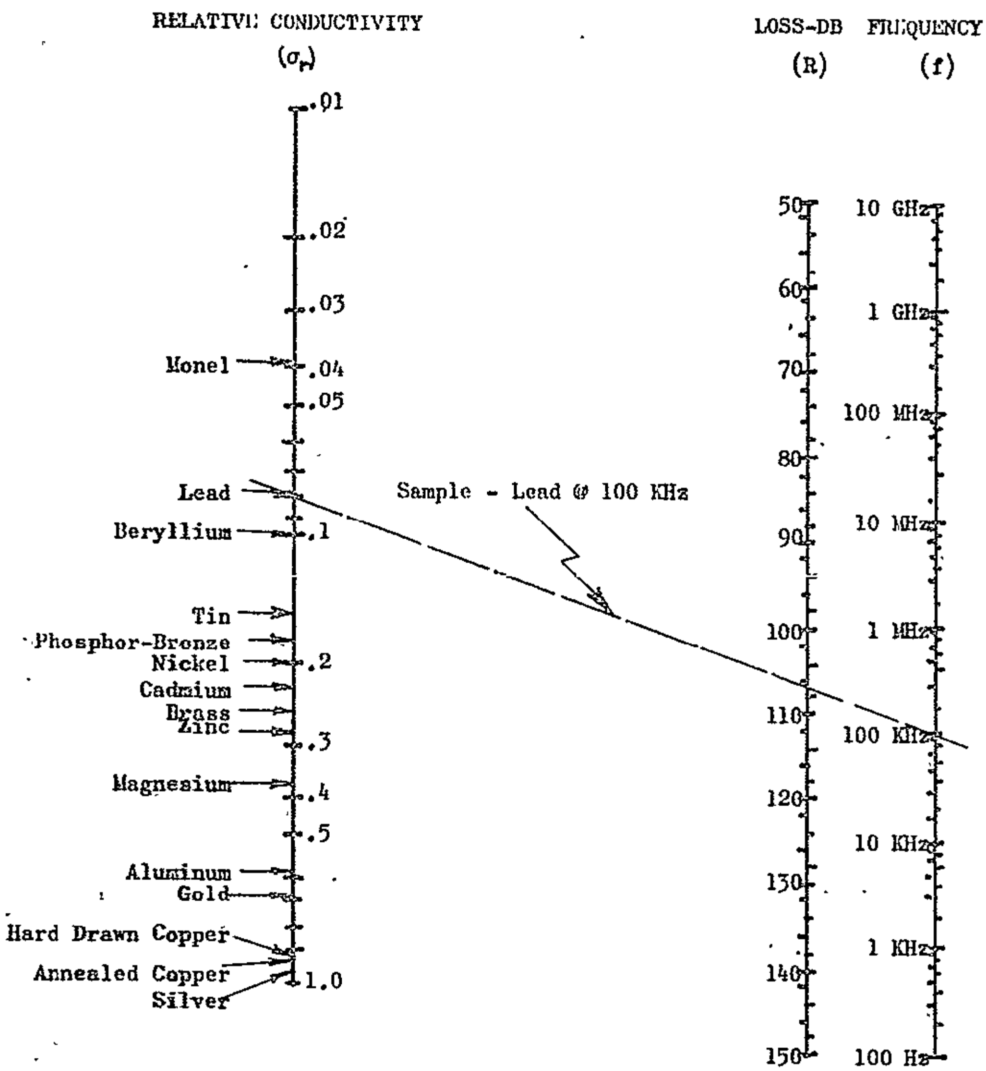

Figure C-3 Nomograph for Reflection Loss - Plane Wave in Solid Nonmagnetic Materials

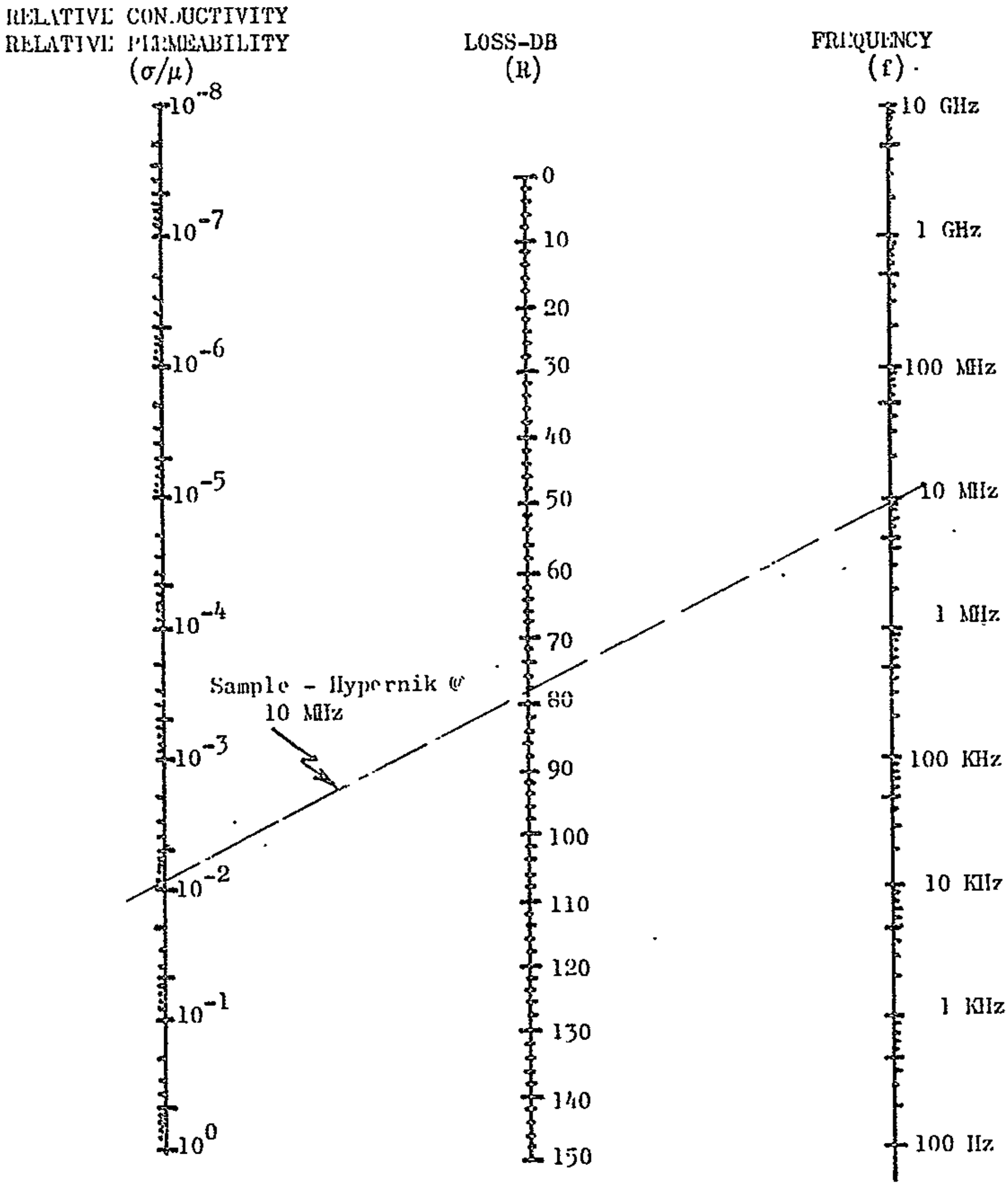

Figure C-4 Nomograph for Reflection Loss of Plane Waves for Solid Magnetic and Nonmagnetic Materials

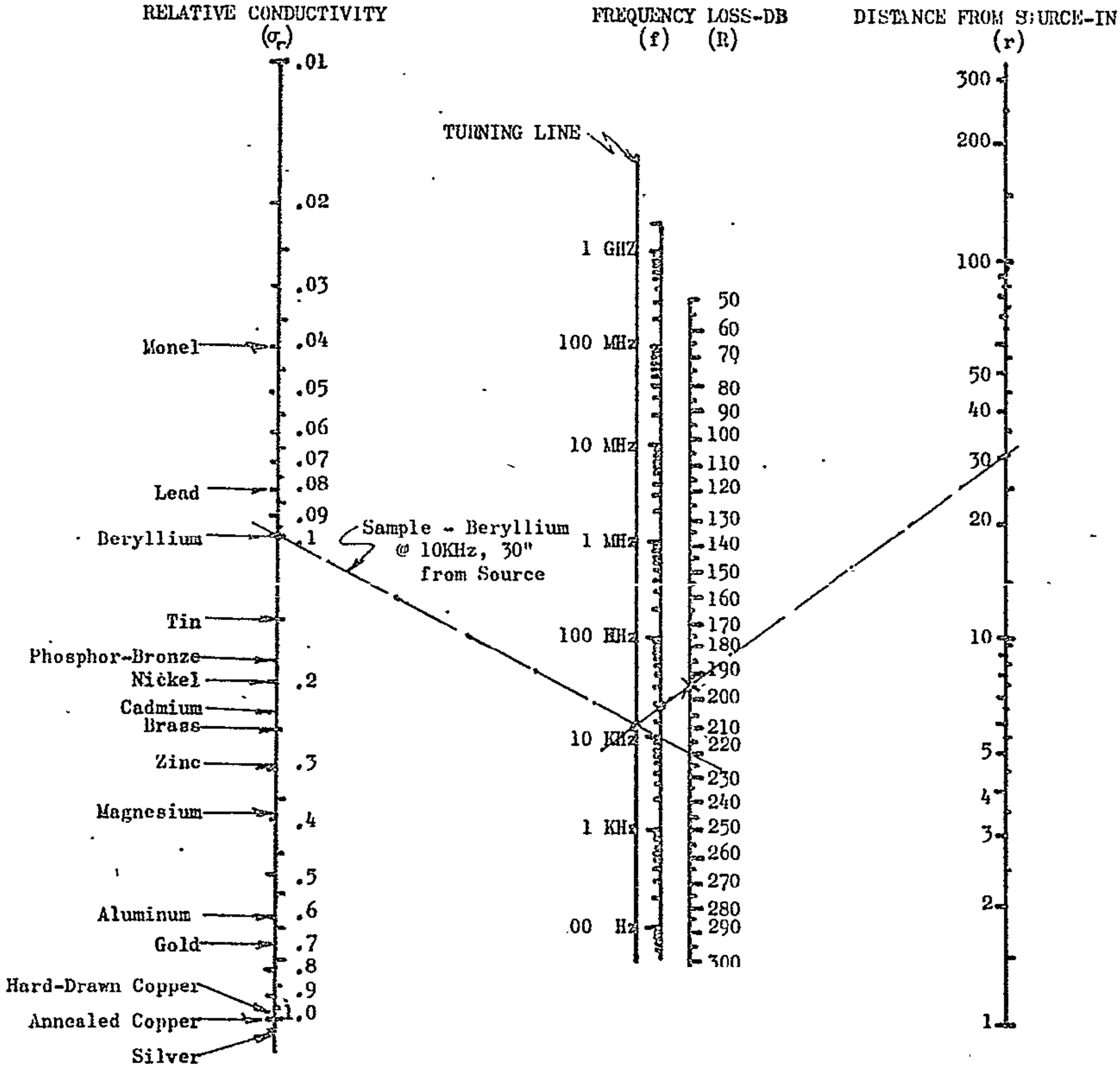

Figure C-5 Nomograph for Reflector Loss of Electrical Field Waves for Solid Nonmagnetic Materials

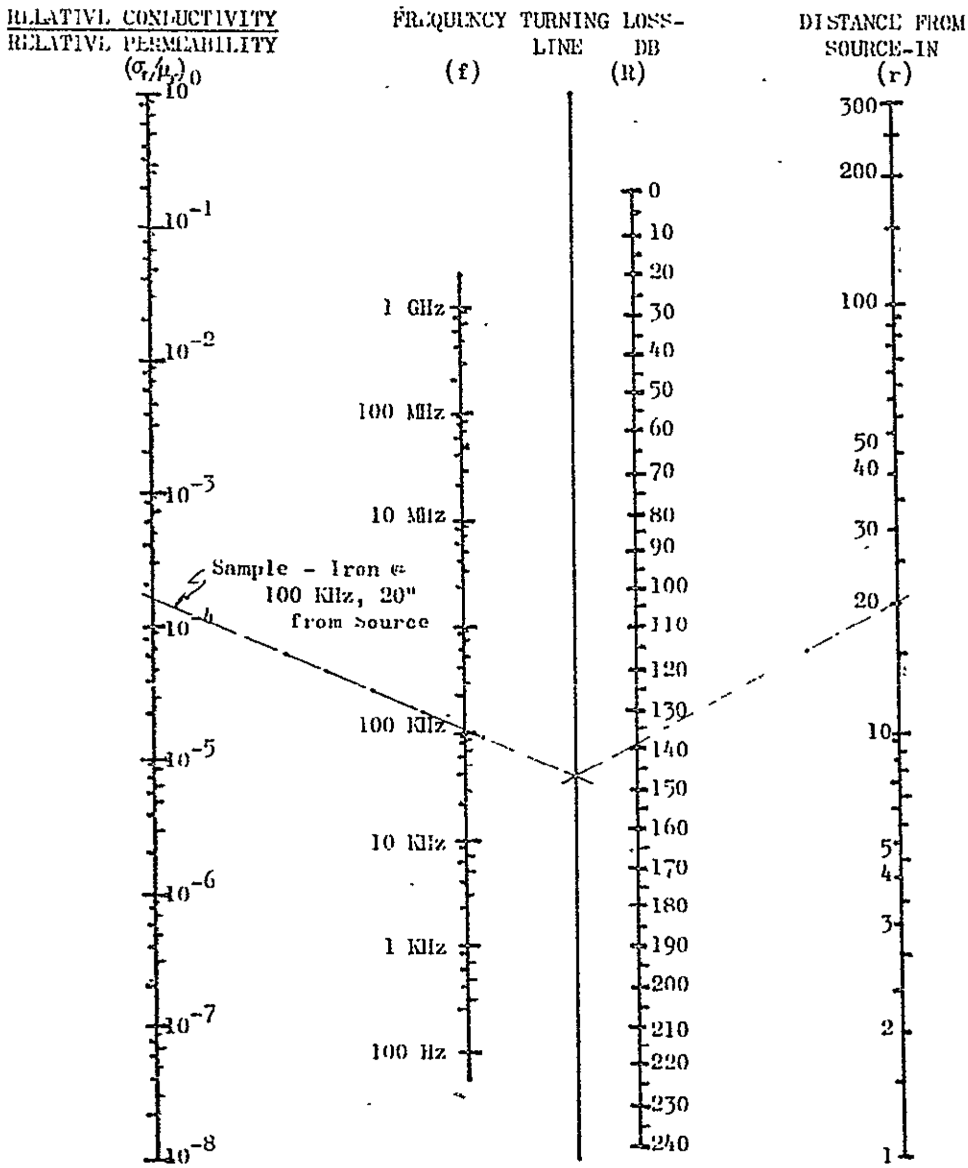

Figure C-6 Nomograph for Reflection Loss of Electric Field Waves for Solid Nonmagnetic Materials

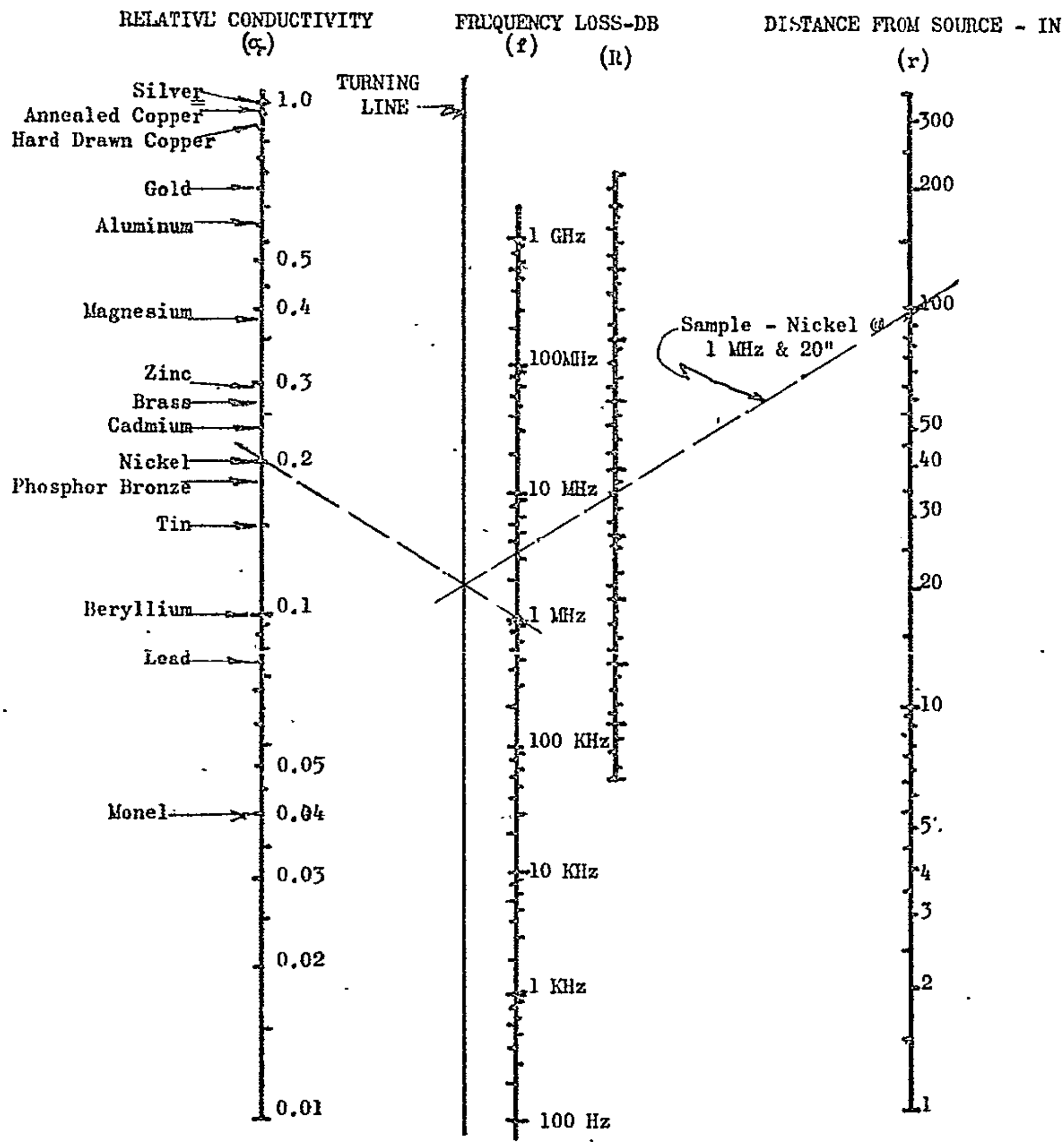

Figure C-7 Nomograph for Reflection Loss of Magnetic Field Waves for Solid Nonmagnetic Materials

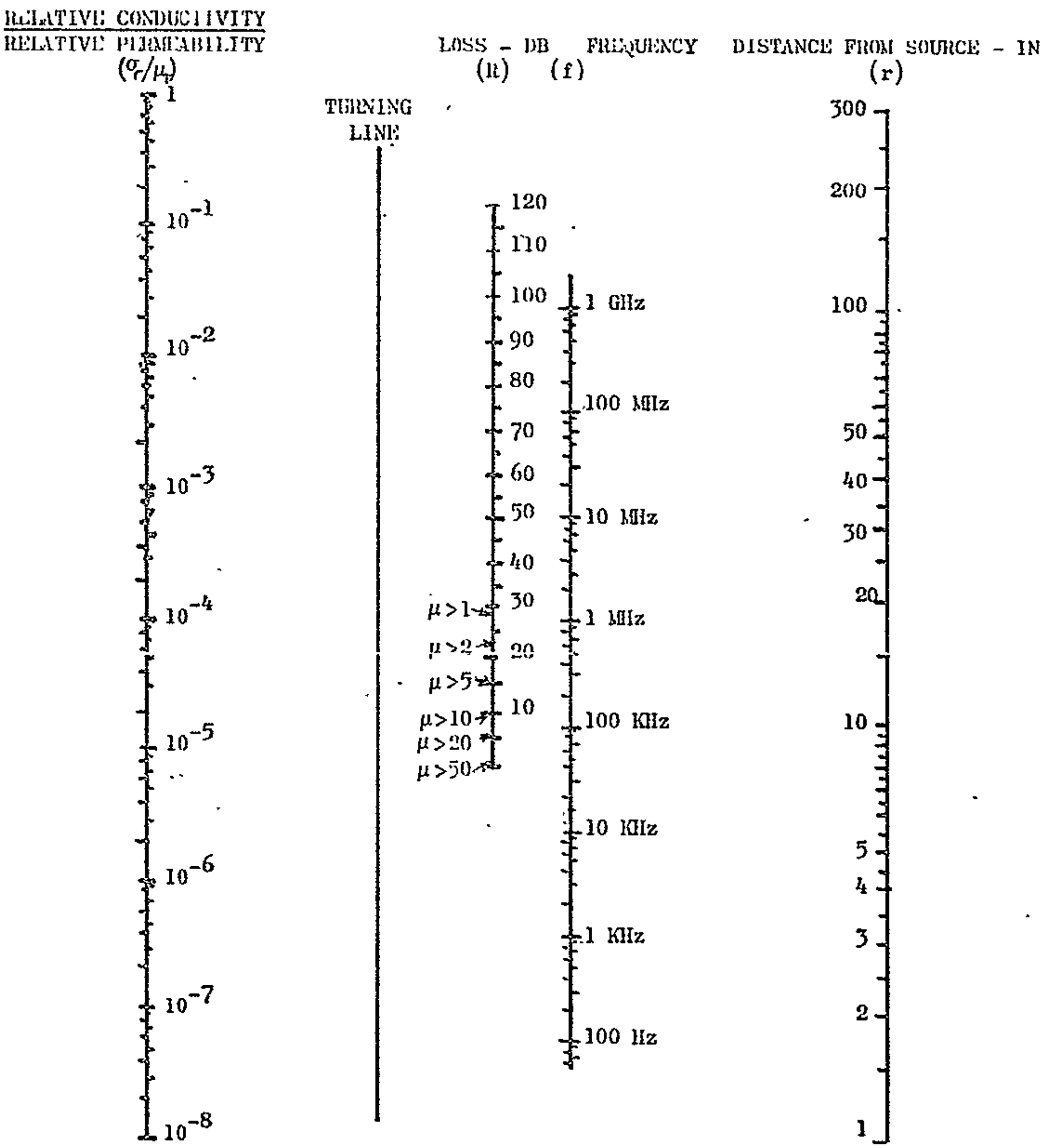

Figure C-8 Nomograph for Reflection Loss of Magnetic Field Waves for Solid Magnetic and Nonmagnetic Materials

C.4 CIRCUIT DESIGN

The role of circuit design in achieving EMC is simply stated as design for minimum generation of EMI, and maximum threshold to minimize susceptibility to the effects of EMI. Layout of circuits can result in improved EMC by separation of mutually interfering components, correct shielding and orientation of components, and adequate decoupling. Considerable improvement of circuit performance can often be realized by providing a ground bus in a chassis so that no intercircuit coupling can result through currents in the chassis metal itself.

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